NEWS from CPSC

U.S. Consumer Product Safety Commission

Office of Information and Public Affairs Washington, DC 20207

FOR IMMEDIATE RELEASE
June 4, 1996
Release # 96-140

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CPSC Releases Study of Protective Equipment for Baseball

"We want kids outside in the sunshine, not inside in an emergency room," said CPSC Chairman Ann Brown.

WASHINGTON, D.C. The U.S. Consumer Product Safety Commission (CPSC) announced today that safety equipment for baseball could significantly reduce the amount and severity of 58,000 (or almost 36 percent of) baseball-related injuries to children each year.

Baseball, softball, and teeball are among the most popular sports in the United States, with an estimated 6 million children ages 5 to 14 participating in organized leagues and 13 million children participating in non-league play. In 1995, hospital emergency rooms treated 162,100 children for baseball-related injuries.

At a press conference at Camden Yards stadium, home of the Baltimore Orioles, CPSC released the findings from its one-year study on the ability of protective equipment, including softer-than-standard baseballs, safety release bases, and batting helmets with face guards, to reduce injuries to children playing baseball.

"CPSC is the federal agency responsible for overseeing the safety of 15,000 different types of consumer products, including sports equipment and products claiming to reduce injuries and increase safety," said CPSC Chairman Ann Brown. "Parents need to know what options they have in protective equipment so they can make the best decisions for their children playing baseball."

Nick Senter, executive director of the Dixie Baseball League, an organization based in 11 Southern states, and Richard Bancells, trainer of the Baltimore Oriole's baseball team, joined Chairman Brown for today's announcement.

Senter said, "Since we began using batting helmets with face guards in the Dixie League, we've seen a drop in both injury rates and insurance rates."

CPSC collected and analyzed data on baseball, softball, and teeball-related deaths and injuries to children to determine specifically how these children were injured and what safety equipment could prevent such injuries. CPSC also studied voluntary safety standards and reviewed published scientific literature evaluating currently available protective equipment.

CPSC analyzed the 88 reports it received of baseball-related deaths of children between 1973 and 1995. It found that 68 of the deaths were caused by ball impact and 13 were caused by bat impact. Of the 68 ball impact deaths, 38 resulted from blows to the chest while 21 deaths were caused by a ball hitting a player's head.

Of the 162,100 hospital emergency-room-treated injuries in 1995, most of the injuries (almost 75 percent) occurred to older children ages 10 to 14. This age group represents about half of the total number of children playing baseball.

Of the total number of injuries to children, CPSC considers about 33 percent severe, including fractures, concussions, internal injuries, and dental injuries. The remaining 67 percent less severe injuries include contusions, abrasions, lacerations, strains, and sprains. More than 50 percent of the children under age 11 who were injured while playing baseball sustained injuries to the head and neck area, while a larger percentage of older children sustained injuries to their arms and legs.

Based on its analyses, CPSC found that three pieces of safety equipment will help reduce injuries.

Softer-than-standard baseballs and softballs, which have a softer, spongier core than standard baseballs and softballs, can reduce ball impact injuries. Face guards that attach to batting helmets and protect the face can reduce injuries to batters.

Safety bases that release from their anchor can reduce sliding injuries. Safety release bases that are based on age, gender, and skill levels of the players provide the best protection.

Conclusions from the CPSC Study:

- Baseball protective equipment currently on the market may prevent, reduce, or lessen the severity of more than 58,000 injuries or almost 36 percent an estimated 162,100 hospital emergency-room-treated, baseball-related injuries occurring to children each year.
- Softer-than-standard balls may prevent, reduce, or lessen the severity of the 47,900 ball impact injuries to the head and neck.
- Batting helmets with face guards may prevent, reduce, or lessen the severity of about 3,900 facial injuries occurring to batters in organized play.
- Safety release bases that leave no holes in the ground or parts of the base sticking up from the ground when the base is released may prevent, reduce, or lessen the severity of the 6,600 base-contact sliding injuries occurring in organized play.

American Academy of Pediatrics

Policy Statement

Pediatrics Volume 93, Number 4 April, 1994, p 690-692

Risk of Injury From Baseball and Softball in Children 5 to 14 Years of Age (RE9409)

AMERICAN ACADEMY OF PEDIATRICS

Committee on Sports Medicine and Fitness

Baseball is one of the most popular sports in the United States, with estimates of 4.8 million children 5 to 14 years of age participating annually in organized and recreational baseball and softball. Interest in and fascination with the sport have grown since the beginning of the 20th century, but it was not until 1965 that the issue of "Little League elbow" raised concern about the safety of the game. Recently, highly publicized catastrophic impact injuries from contact with a ball or bat have raised new safety concerns. These injuries provided the impetus for this review of the safety of baseball for 5- to 14-year-old participants. The discussion focuses principally on baseball, but softball is considered in accord with the availability of relevant literature. This statement mainly concerns injuries during practices and games in organized settings; players and bystanders also can be injured in casual play.

The term Little League elbow was used in 1965 to denote radiologic evidence of fragmentation of the medial epicondylar apophysis and osteochondrosis of the head of the radius and capitellum.[1,2] Subsequent studies of children 12 years old and younger[3,4] have found a substantially lower incidence of abnormalities than originally described.[1,2] Early detection and intervention seem to permit the complete resolution of symptoms and underlying structural abnormalities.[5] More serious abnormalities become more common after the age of 13 years.[6-8] The role that repetitive throwing in 5- to 14-year-old children may play in the evolution of elbow overuse injuries at an older age remains to be determined. In response to concern about Little League elbow, many youth leagues have attempted to limit the stress placed on young pitching arms. For example, Little League Baseball, Inc limits pitchers to a maximum of six innings of pitching per week and requires mandatory rest periods between pitching appearances.[9] Instruction in proper pitching mechanics is another way to prevent serious overuse throwing injuries.[5,10]

The overall incidence of injury in baseball ranges between 2% and 8% of participants per year. Most injuries are minor soft tissue trauma, usually to the face and upper extremity.[11,12] Sliding is the cause of one third of the injuries to the lower extremity. In softball and baseball, the Velcro-stabilized breakaway base significantly reduces this risk.[13,14]

Recently, concern has been raised about injuries to the eye.[15-17] Baseball seems to be the leading cause of sports-related eye injuries in children, and the highest incidence occurs in those 5 to 14 years of age. Approximately one third of baseball-related eye injuries result from being struck by a pitched ball. As a result, in this age group, the Sports Eye Safety Committee of the National Society to Prevent Blindness has recommended the use of batting helmets with polycarbonate faceguards that meet Standard F910 of the American Society for Testing and Materials.[18] These cover the lower part of the face from the tip of the nose to below the chin; they also protect against injuries to the teeth and facial bones. Functionally one-eyed athletes (those with best corrected vision in the worst eye of <20/50) must use these faceguards; they also must protect their eyes when fielding by using polycarbonate sports goggles. Eye protection also may be particularly important for young athletes who have had previous surgery or serious eye injury.

Recently the potential of catastrophic injury resulting from direct contact with a bat, baseball, or softball has received publicity. Deaths have occurred from impact to the head resulting in intracranial bleeding and from nonpenetrating blunt chest impact probably causing ventricular fibrillation or asystole.[19-21] Statistics compiled by the US Consumer Product Safety Commission[11,22,23] indicate that in the 8-year period from 1973 to 1980, 40 baseball- or softball-related deaths were reported in children 5 to 14 years of age. Of these deaths, 21 resulted from head and neck injuries, 17 from nonpenetrating impact to the chest, and 2 from other causes, an average of 5 deaths per year. In the 5-year period of 1986 through 1990, 16 baseball- or softball-related deaths were recorded, an average of 3.3 per year. Eight deaths were due to head and neck injuries, seven were caused by chest impact, and one was due to other causes. It would seem that there has been no significant recent change in impact-related deaths in baseball and softball, but conclusions must be tempered by differences in the sources for data surveillance for the two periods studied.[11,22,23]

Direct contact by the ball is the most frequent cause of death and serious injury in baseball. Children 5 to 14 years of age seem to be uniquely vulnerable to blunt chest impact, because their thoraces may be more elastic and more easily compressed.[24,25] Preventive measures to protect young players from direct ball contact include utilization of batting helmets and face protectors while at bat and on base; utilization of the catcher's helmet, mask, and chest and neck protectors; the elimination of the on-deck circle; and the protective screening of dugouts and benches. Future equipment may include chest protectors for batters and pitchers if this equipment can be developed in an efficacious and acceptable manner. Modifications in the hardness and compressibility of softballs and baseballs have been developed for use by children of different ages, with the intent of reducing the force of impact while maintaining performance characteristics. The National Operating Committee on Standards for Athletic Equipment (NOCSAE) has developed standards for these softer baseballs.[26] Studies evaluating their playing characteristics and capacity to reduce injury are in progress; but, at the time this review was completed, it was not yet clear whether these balls offer an advantage in injury prevention.

Compared with older players, children less than 10 years of age often have less coordination, slower reaction times, a reduced ability to pitch accurately, and a greater fear of being struck by the ball. Some developmentally appropriate rule modifications are therefore advisable for this age group, including the use of an adult pitcher, a pitching machine, or a batting tee; the avoidance of head-first sliding; and perhaps the use of softer balls, if they are proven to be safer than standard ones.

There have been anecdotal reports of rare but serious cervical spine injuries occurring when a player slides head-first, hitting an opponent with the top of the helmet. This injury is similar to that caused by spearing in football. If further injury surveillance confirms the need, such sliding may need to be banned in players older than 10 years.

Much of the injury research has concerned baseball, or has not differentiated between baseball and softball. Injury risks seem to be similar in softball, except that softball players are less likely to incur overuse injuries of the pitching arm. Therefore, the same recommendations for injury prevention in baseball apply to softball, except for limitation on pitching.

RECOMMENDATIONS

The American Academy of Pediatrics recommends:

1. Pediatricians may be supportive of the desire of 5- to 14-year-old children to participate in baseball and softball. Catastrophic and chronically disabling injuries are rare and do not seem to have been increasing in frequency in the past decade. Surveillance of baseball and softball injuries should be continued.
2. All preventive measures should be employed to protect young baseball pitchers from disabling throwing injuries. These measures include a restriction on the amount of pitching, in both organized and informal settings; instruction in proper biomechanics; and education of parents, coaches, and children to permit early diagnosis and treatment of overuse pitching injuries.
3. All preventive measures that can reduce serious and catastrophic injuries should be employed in both baseball and softball. These include the use of approved batting helmets; the catcher's helmet, mask, and chest and neck protectors; and rubber spikes. The elimination of the on-deck circle, the protective fencing of dugouts and benches, and the use of breakaway bases are also recommended.

Protective equipment should always be sized properly and well maintained. These preventive measures should be employed in both games and practices and in organized and informal participation. Developmentally appropriate rule modifications such as alternative pitching techniques and the avoidance of head-first sliding should be implemented for children less than 10 years of age.
4. Baseball and softball players should be encouraged to reduce the risk of eye injury by wearing polycarbonate eye protectors on their batting helmets. These should be required for the functionally one-eyed athlete (best corrected vision in the worst eye of <20/50) or for athletes with previous eye surgery or severe eye injuries, if their ophthalmologists judge them to be at increased risk of eye injury. The latter two groups should also protect their eyes when fielding by using polycarbonate sports goggles.
5. Consideration should be given to utilizing low-impact NOCSAE-approved baseballs and softballs for children 5 to 14 years of age, if these balls demonstrate satisfactory playing characteristics and reduce injury risk. Children younger than 10 years of age should be particularly encouraged to use the lowest impact NOCSAE-approved balls because these children tend to be less skilled and coordinated. A variety of studies should be undertaken to determine the efficacy of low-impact balls in reducing serious impact injuries. Research should be continued to develop other new, improved, and efficacious safety equipment.

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———— This statement has been approved by the Council on Child and Adolescent Health. The recommendations in this statement do not indicate an exclusive course of treatment or serve as a standard of medical care. Variations, taking into account individual circumstances, may be appropriate.

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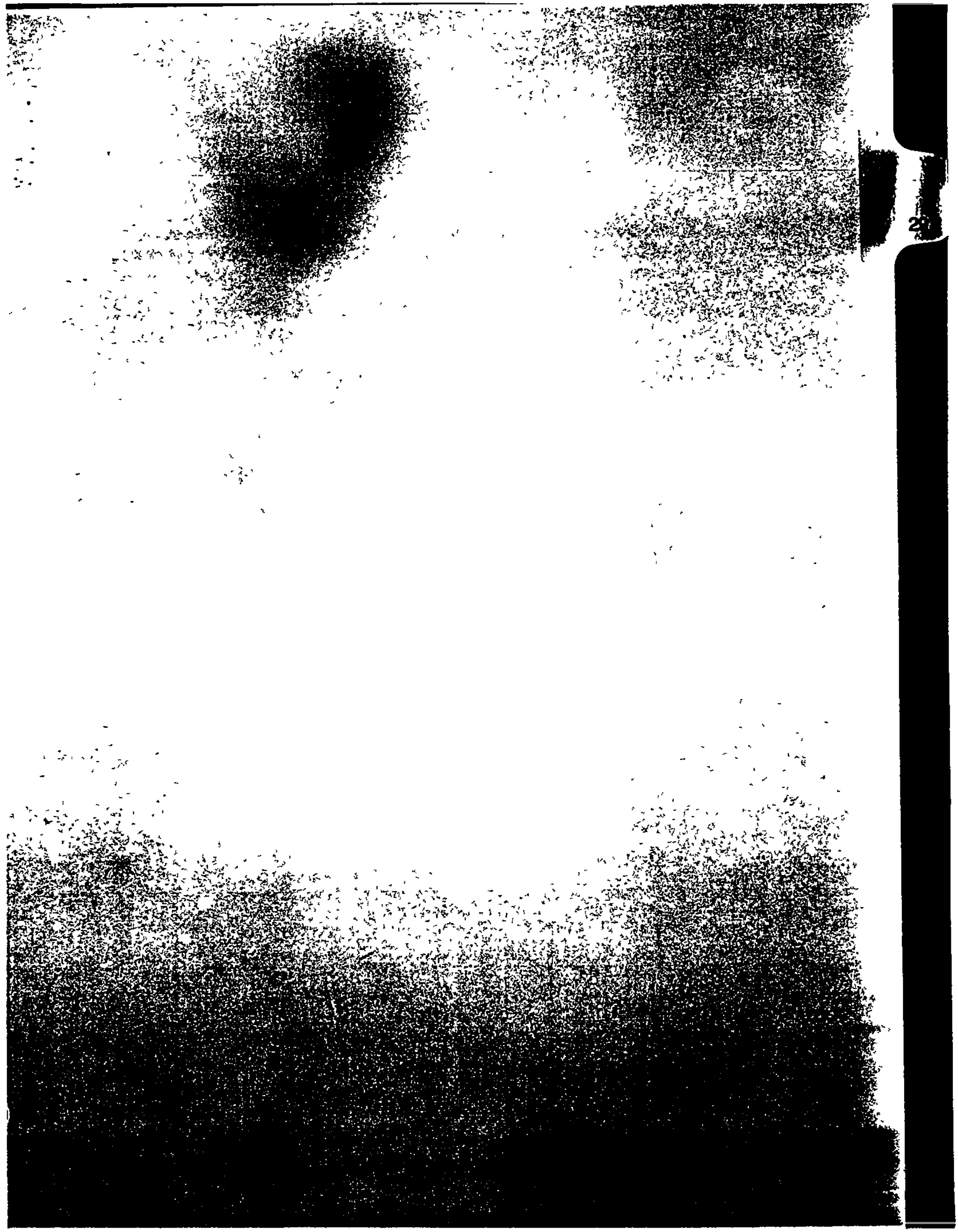

National Institute for Sports Science & Safety

November 13, 1997

Ted Breidenthal
NCAA
6201 College Boulevard
Overland Park, Kansas 66211-2422

RE: 1) Final Report for the NCAA Research Program on Bat and Ball Performance
2) Proposal for a Rapid Compliance Program for Baseball Balls and Bats

Dear Ted,

The enclosed Final Report for the NCAA Research Program on Bat and Ball Performance is the original copy. I have retained a copy for my records, but I will not disperse it until I have your approval. Even with that, my copy is not a good one and if possible I think it would be best if the NCAA could disseminate high quality copies to those who request them. If the NCAA does decide to disseminate it, I would appreciate 15 copies that I can send to those who helped.

While the Report is long I have tried to do my best to list all of the important facts in the Summary section. More importantly than this, perhaps, is the Recommendations section. Clearly, while I believe the Report is the most thoroughly assembled document on this subject, it does not give specific recommendations for acceptable levels of bat-ball performance nor does it specify improvements in the test methodology. These were specifics that were beyond the scope of this program.

Much remains to be done in this area, but much of what needs to be done requires significant funding and effort. It remains unclear how the ASTM/Brandt methodology will or will not perform at realistic velocities and it remains unclear if the Baum Hitting Machine can be operated cost effectively by a second party. Much of this work will hopefully progress soon. However, I now believe strongly that much more can be done immediately and with minimal costs to the NCAA. (It will require a formal statement by the NCAA mandating compliance by all manufacturers as part of the NCAA specifications). In response to this belief, Rick Greenwald, Ph.D. and I have proposed A Rapid Compliance Program for Baseball Balls and Bats. A copy of this proposal is also included.

It is important to note that the Rapid Compliance Program for Baseball Balls and Bats will collect and analyze data on all bat and ball models used in NCAA play. This data will be generated from tests required of manufacturers. Some of these tests are the existing NCAA specifications and other tests are additional ones, such as higher velocities for ball COR measurements and the Baum Hitting Machine. Thus, this compliance program is not a proposal for a new standard test methodology, but, more importantly at this time, will generate the most exhaustive database available on the products used in NCAA. Such data can then be used as guidelines for future decisions by the Rules Committee and will also ensure product compliance to existing specifications.

I would like to thank you for the opportunity to work with you on this fascinating area. I hope that our efforts have been helpful to you and your associates and I hope we can continue working on these issues.

Sincerely,

J.J. Trey Crisco, Ph.D.

encl.

A RAPID COMPLIANCE PROGRAM FOR BASEBALL BATS AND BALLS

PREPARED FOR:

NCAA
6201 College Boulevard
Overland Park, Kansas

BY

National Institute for Sports Science and Safety
54 Oriole Avenue
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PROJECT # NISSS9703
November 12, 1997

PROGRAM INITIATION DATE: Date of Approval
PROGRAM COMPLETION DATE: Bi-Annual Reports until Termination

PROTOCOL APPROVAL

STUDY DIRECTOR	J.J. Trey Crisco, Ph.D.	Nov 16 1997 Date
SPONSOR REPRESENTATIVE	Ted Breidenthal, NCAA	Date
ALTERNATIVE SPONSOR REPRESENTATIVE		Date

A RAPID COMPLIANCE PROGRAM FOR

BASEBALL BATS AND BALLS

PREPARED FOR:

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PROGRAM INITIATION DATE: Date of Approval
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PROTOCOL APPROVAL

STUDY DIRECTOR	J. J. Trey Crisco, Ph.D.	Nov 16, 1997 Date
SPONSOR REPRESENTATIVE	Ted Breidenthal, NCAA	Date
ALTERNATIVE SPONSOR REPRESENTATIVE		Date

Title: A Rapid Compliance Program for Baseball Balls and Bats
Principal Investigators: J.J. Crisco Ph.D. and R.M. Greenwald, Ph.D.,
National Institute for Sport Science and Safety (NISSS)
Providence, Rhode Island

Introduction

The bat-ball contact at game velocities is a complicated mechanical and biomechanical impact event. The available literature on this topic is limited, but growing. Laboratory test methods have been developed to measure the performance of the ball and the bat (ASTM/Brandt, Baum Hitting Machine (BHM)). These methods have proved to be an engineering challenge. The ASTM/Brandt method is presently the industry standard for predicting bat performance, but is limited in its ability to predict performance under game conditions. While the BHM is a more sophisticated apparatus for studying the ball-bat impact and is most likely a better predicator of actual field events, its use as a *standard* test methodology remains to be demonstrated. The existing methodology for estimating ball performance is limited. A complete discussion of the advantages and limitations of each method can be found in the Final Report of the NCAA Research Program on Bat and Ball Performance (Crisco, 1997).

An immediate solution to many of the limitations of the existing test methodologies is not possible but is being addressed by others such as the group at the University of Massachusetts, Lowell Campus.

Regardless of the performance level selected by the NCAA Rules Committee and the associated test methodology, there is a paucity of documentation on bat and ball performance to the *existing* NCAA guidelines. Further, new methodology such as the BHM have not yet been utilized to study the range of baseball and baseball bats presently used in NCAA.

Purpose

The purpose of this program is three fold:

1. To place a third party (NISSS) in the role of collecting and analyzing data from manufacturers (first party) and testing laboratories (second parties).
2. To rapidly build a specification and performance database on all baseball balls and baseball bats presently used in NCAA.
3. To analyze this database to give the NCAA the most comprehensive understanding of ball and bat performance available to any party.

Deliverables to the NCAA

1. A complete catalogue of all specifications and performance criterion of all baseball balls and bats used in NCAA by a third party (NISSS).
2. A full analysis of all performance data allowing specific comparison of test methodologies.

Procedures

Manufacturers will be required to test their products using ASTM/Brandt and BHM methodology. Testing can be performed at any location, such as New York University, Fluid Technologies Inc., Detroit Testing Labs, UMASS - Lowell, etc.. The specific tests to be conducted on balls and bats include all presently used methodology and include: ball specification and COR measurements, and bat specifications and batted ball velocities.

Manufacturers will be required to submit all data in a specified format to NISSS.

NISSS will catalogue and analyze all submitted data.

NISSS will develop a bi-annual presentation of all data for the NCAA. Data will be *blinded* to product name and manufacturer information in all such presentations.

Time Frame

The Compliance Program can be implemented within two months of agreement.

Budget

Costs to the NCAA will include an annual charge of $4,500 plus travel costs for the two principals to meet with the NCAA.

Manufacturers will be required to cover *all* testing costs.

All NISSS operating costs will be covered through manufacturers on a per model cost ($250 for each ball model and $750 for each bat model).

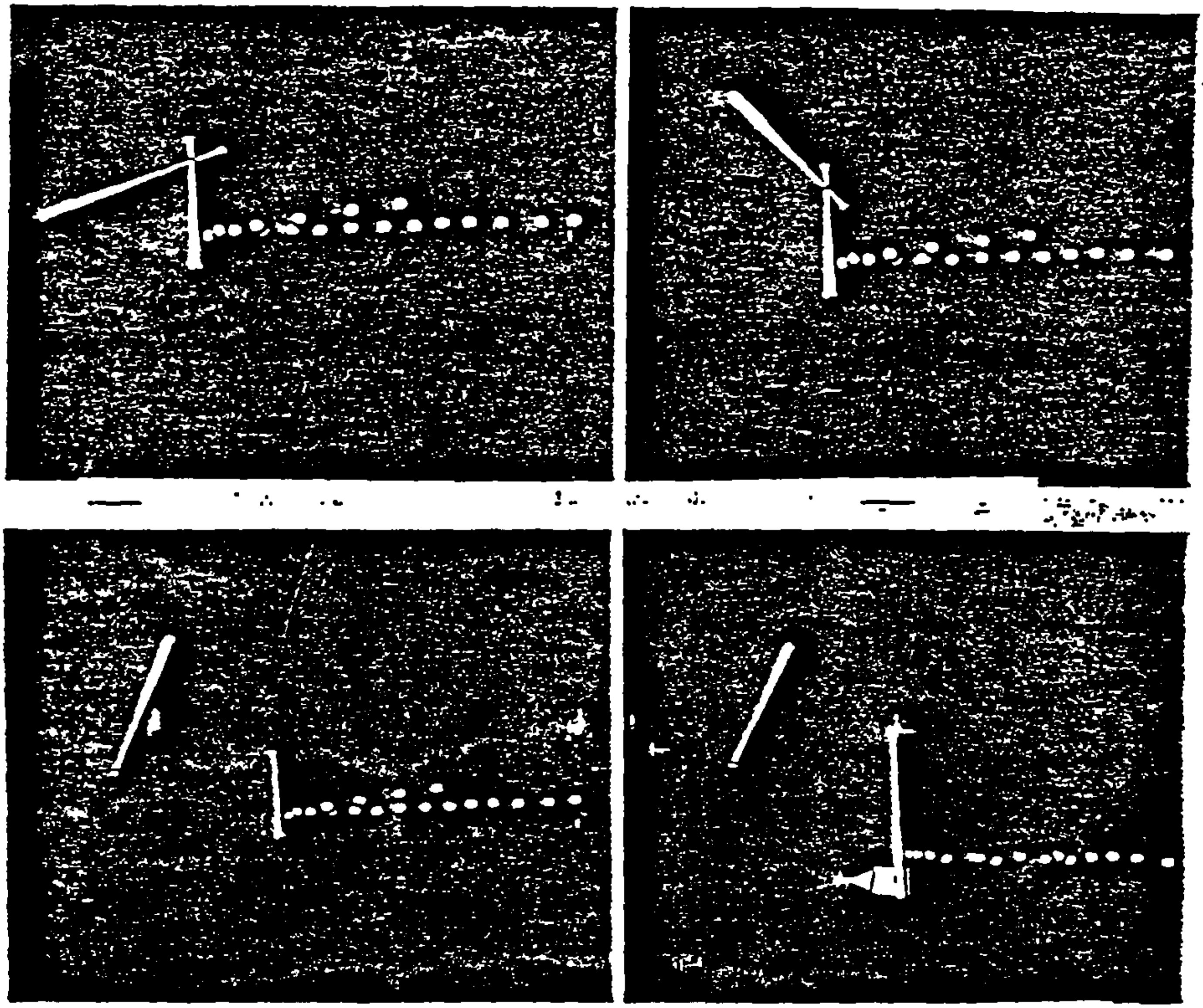
November 12, 1997

FINAL REPORT

NCAA Research Program on Bat and Ball Performance

October, 1996 - September, 1997

Program Director: J.J. Trey Crisco, Ph.D., Providence, Rhode Island



Cover Figure. Bat motion in the laboratory (Top) is constrained to an axis of rotation that is fixed (purple point) about the handle. *The actual motion of a bat during a swing is highly complex. In a typical swing (Bottom), the rotation axis* (represented by the purple points in the plane of the bat) lies inward and offset from the handle. During the swing, the rotation axis moves forward and changes its location in space (data provided by Fleisig et al., 1997). The significance of these differences in bat motion on predicting bat performance is unknown.

FINAL REPORT

NCAA Research Program on Bat and Ball Performance

October, 1996 - September, 1997
Program Director: J.J. Trey Crisco, Ph.D., Providence, Rhode Island

RECOMMENDATIONS

R1) A rigorous compliance program for documenting ball and bat performance should be adopted immediately. It is suggested that such a program require manufacturers to test balls and bats using existing ASTM methodology and using the Baum Hitting Machine (BHM) methodology. The data from all tests should be collected and analyzed by a third party. Manufacturers should cover all costs for testing and data collection and analysis.

R2) A scientific field study on bat swing and batted ball velocities should be undertaken using advanced methods and statistically sufficient numbers of samples. This would yield crucial data that could serve as the "*gold-standard*" for evaluating laboratory test methods.

R3) Monitoring of injuries by the NCAA Injury Surveillance System (ISS) should be expanded from the present sampling levels of 14% and 18% of the baseball and softball programs, respectively, to include a greater percentage of softball and baseball programs.

R4) A scientific meeting on bat-ball performance and related issues should be hosted. All interested parties should be encouraged to submit their studies for presentation at this or other scientific conferences such as ASMI's Annual Injuries in Baseball Course.

SUMMARY

1.1) While scientific studies can provide an understanding of the factors leading to injury from the batted ball, only the people of baseball and softball (i.e. the players, coaches, governing bodies, etc.), not science, can define *what risk of injury due to the batted balls is acceptable*. Thus, what risk is acceptable is the major issue in regulating bat and ball performance, and the specifics of a standard test methodology are secondary.

1.2) The exact level of acceptability (typically defined in terms of one or more standard laboratory measurements such as maximum batted ball velocity) will be arbitrary, but should lie within values suggested from scientific studies.

1.3) Existing standards for bat and for ball performance are based upon practical experience with little scientific basis.

2.1) Extensive data from studies on impact injuries to a wide range of tissue (e.g. muscle, bone, brain) and on the reaction times of subjects clearly indicate that increases in impact velocity would increase the severity and the frequency of injury.

2.2) Injuries from the batted ball have occurred with the use of wood bats and traditional baseballs.

2.3) Baseball and softball remain the safest sports (as defined by the frequency of injury) of those included in the NCAA Injury Surveillance System (ISS).

2.4) The NCAA ISS reports that the frequency of injuries from the batted ball has remained constant since 1992.

3.1) *No rigorous scientific studies on bat performance have yet been published.* The limited data that are available indicate that modern non-wood bats outperform comparable wood bats, as defined by maximum batted ball velocity. How much performance is actually obtained in the field depends upon numerous factors and has not yet been rigorously determined.

3.2) The existing standard test method for estimating bat performance (ASTM/Brandt), in its present form, is unlikely to be capable of predicting actual batted ball velocities in baseball or fast-pitch softball. This opinion is based upon the fact that the test pitch velocity is set at 60 mph (0 mph swing velocity), as compared to actual approach velocities of at least 150 mph (i.e. swing velocity plus pitch velocity). Data provided by two laboratories indicate that this limitation cannot be simply corrected by increasing pitch velocity. There was a significant variability in the results on the same bat model from three laboratories.

The Baum Hitting Machine (BHM) apparatus was recently subjected to an independent evaluation and is considered the state-of-the-art for measuring both bat and ball performance. It provides the capabilities of measuring batted ball velocity for specified combinations of swing and pitch velocities. Inter-lab variability was not addressed in the evaluation. The BHM should be considered the most sophisticated apparatus available for studying bat-ball impact performance. The practicality of this apparatus as a standard test methodology remains to be demonstrated.

4.1) *Several scientific studies have demonstrated that the existing test methodology (ASTM), in its present form, is insufficient for predicting ball performance at realistic velocities.*

4.2) An improved standard test methodology for predicting ball performance is warranted and should be the most timely and cost effective first step to improving the regulation of bat-ball performance.

5) Numerous factors affect batted ball velocity, including bat weight and weight distribution. Bats that are lighter and more "handle-heavy" can be swung faster. Bat speed was shown to have a stronger correlation with bat moment of inertia (inertia) than bat weight. This suggests that it would be more effective to regulate bat inertia than bat weight. The effects of weight and weight distribution on swing mechanics and the ability of a player to alter their swing mechanics with practice have not been studied.

NOTE.

The above recommendations and summary also apply to softball, however, there is less history in softball product design and even less available data on softball bats and balls. However, several other governing bodies of softball are already addressing the same concerns that motivated this Research Program.

The above Recommendations and Summary are based upon the presently available published data. More scientific studies need to be performed and <u>published</u>. It must be appreciated that new findings may either support or correct our present knowledge, potentially leading to modifications of the above Recommendations and Summary.

COMMENT. There is clearly a paucity of rigorous scientific studies on ball-bat impact and performance. A lack of funding is one of the reasons for this. In the opinion of the Program Director (JJC), a lack of communication between the NCAA, manufacturers, and scientists has also contributed to limiting progress in this area. Further progress in this area requires that the NCAA, MLB, manufacturers, and scientists pool their resources, work together, and consider *publication of findings* as the only appropriate means for discussing and critiques results.

ACKNOWLEDGMENTS

Sincere thanks to those, listed in no special order, who have contributed to this program:

Advisory Panel
- Robert Adair, Ph.D., Yale University
- Terry Bahill, Ph.D., University of Arizona
- Allen Burton, Ph.D. and Paul Cassidy, University of Minnesota
- Clarence Calder, Ph.D., Oregon State University (Deceased)
- Sue Kyle, Ph.D., Consumer Product Safety Commission

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- Jim Sherwood, Ph.D. and Tim Mustone, UMass-Lowell
- Larry Fallon, PE, Sports Engineering
- Robert Collier, Ph.D., Consultant; Lecturer, Dartmouth College
- Jay Bhatt, Ph.D., Hillerich & Bradsby Co., Inc.
- Rick Greenwald, Ph.D., Orthopaedics Biomechanics Insititute
- Associates at Fluid Technologies, Inc.
- Associates at Baum Research and Development

Participating Laboratories
- Orthopaedic Biomechanics Insititute
- Hillerich & Bradsby, Inc.
- Fluid Technologies, Inc.
- Baum Research and Development
- NCAA Sport Sciences

Funding/Donations
- MLB
- NCAA
- Hillerich & Bradsby Co., Inc.
- Easton
- Worth
- Department of Orthopaedics, Rhode Island Hospital

BACKGROUND

Aluminum alloy bats were originally introduced into collegiate baseball in the mid 1970's as a cost-effective alternative to wood bats. While performance of the early alloy bats may have been limited, improving bat performance became a principle design objective for manufacturers as a justifiable approach for gaining market shares. The first standard requirement on bat design supported by the manufacturers went in to effect in 1986 and set the minimum bat weight as five units less than its length (i.e. a 33 in. bat could not weigh less than 28 oz.). Changes in bat design continued rapidly and a preliminary limit on bat performance (i.e. the liveliness of the bat in terms of the maximum batted ball velocity) was proposed by the manufactures and adopted by the NCAA in 1995. The reasons for establishing such a limit were growing concerns that injuries from the batted ball will increase as bat performance improves and concerns of the imbalance between hitting and pitching.

Beginning in October of 1996 and concluding in September of 1997, this Research Program was established by the NCAA *to re-evaluate the preliminary limits on bat and ball performance and to critique other issues related to performance.*

The Research Program was formulated as a goal driven program and five specific aims were defined:

AIM 1. To determine the injury patterns from the batted ball.
AIM 2. To evaluate what response time is necessary to avoid impact from a batted ball.
AIM 3. To evaluate existing test methods for predicting ball performance.
AIM 4. To evaluate existing test methods for predicting bat performance.
AIM 5. To determine the effects of bat mass and inertia on swing velocity.

To address these aims, several studies were conducted under this program (Fallon et al., 1997; Cassidy and Burton, 1997; Hendee et al, 1997; Fleisig et al., 1997; Koeing et al., 1997; Greenwald and Crisco, 1997). In addition, two existing methods (Brandt, 1994/ASTM, 1996; Baum, 1997) for measuring bat performance were reviewed. The final reports of the studies that were available at this time are provided in the Appendix.

This Final Report is an attempt to collect and to report the findings of this Research Program. The Report is structured into two main sections one on injury and one on ball and bat performance. We have attempted to report the findings as objectively as possible. It should be clear and it will be obvious that the Program Director places significant weight on the formal publication of results and opinions. Where possible, we have avoided making or supporting any conclusions that are not based on publicly available documents. The lack of published scientific studies was the most significant limitation and obstacle to this entire program.

There are numerous limitations to this Research Program. In general, this Program was neither designed to develop new standard test methodologies nor was it designed to evaluate ball and bat performance of existing products. Specific limitations to each methodology and study are hopefully provided in the body of the Report, where appropriate. This Program did not address the issue that non-wood bats may have altered the balance between offense and defense. While batted ball velocity was the primary quantitative measurement of bat performance examined in this report, the distance the ball travels was not addressed. How far a ball can travel requires a significant effort into the aerodynamics of the ball which is beyond the scope of this report. Those interested in this area are encouraged to begin by reading the texts by Adair (1994) and Watts and Bahill (1990).

Finally, and most importantly, I would again like to acknowledge and to thank those who have contributed to this report.

INJURY

One of the major concerns with increases in batted ball velocities due to improved bat and ball performance is the risk of injury. The most specific concern is the risk of injury to pitchers who are unable to react fast enough to protect themselves. To address this concern of injury four separate issues were investigated. The first issue was to determine the injury patterns from the batted ball (Aim 1). Second, was to determine what response times are needed to allow a player to react to a batted ball and avoid injury (Aim 2). Third, a brief summary of the known effects of increased impact velocity on the severity and the frequency of injury are presented. Fourth, an approach to setting standards for injury prevention are discussed.

AIM 1. To determine the injury patterns from the batted ball.

Introduction

This Aim sought to evaluate the injury data and injury patterns associated with contact from the batted ball. The only injury data base available for such an evaluation is the NCAA Injury Surveillance System (ISS). A brief description of the NCAA ISS was extracted from the ISS Fact sheet and is provided below. Requests for details of the ISS should be directed to Randy Dick, Assistant Director of Sports Sciences, NCAA.

The NCAA ISS was developed in 1982 to provide current and reliable data on injury trends in intercollegiate athletics. Participation in the NCAA ISS is voluntary and limited to approximately 900 schools for 15 sports. For the data used in this study, 110 of 760 baseball programs participated and 125 of 702 softball programs participated. Therefore, it is important to emphasize that this does not identify EVERY injury that occurs at the NCAA institutions in a particular sport. Rather, it collects a sampling that is representative of a national cross-section of institutions. The data are recorded by certified and student athletic trainers from participating institutions. Information is collected from the first official day of preseason practice to the final tournament contest. The data are analyzed using two specific measures: Athletic Exposures and Injury Rate.

Athletic Exposure. An athletic exposure (A-E) is the unit of risk in the ISS and is defined as one athlete participating in one practice or game where he or she is exposed to the possibility of athletic injury.

Injury Rate. An injury rate is simply the ratio of the number of injuries in a particular category to the number of athletic exposures in that category.

The analysis conducted here examined injuries from the batted ball in games only. Data from practices were excluded because of the potential for extraneous circumstances. The analysis was performed using the data available from the NCAA ISS for both softball and baseball. Although the NCAA ISS was developed in 1982, data on injuries from the batted ball are only available from 1992 to 1996.

Review

The data from the NCAA ISS were analyzed and plotted in Figures 1 and 2 below.

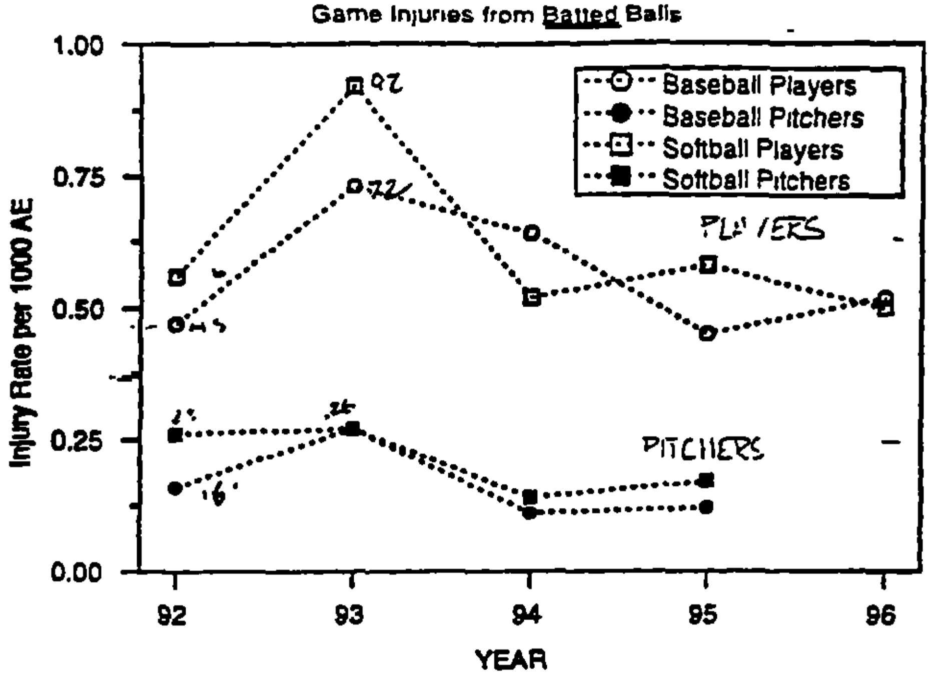


Figure 1. *Injury rate for players and for pitchers* *<u>injured by the batted ball</u>* *during games for the years the data were available.* There were no significant changes with time. Injury rate for both baseball and softball were similar.

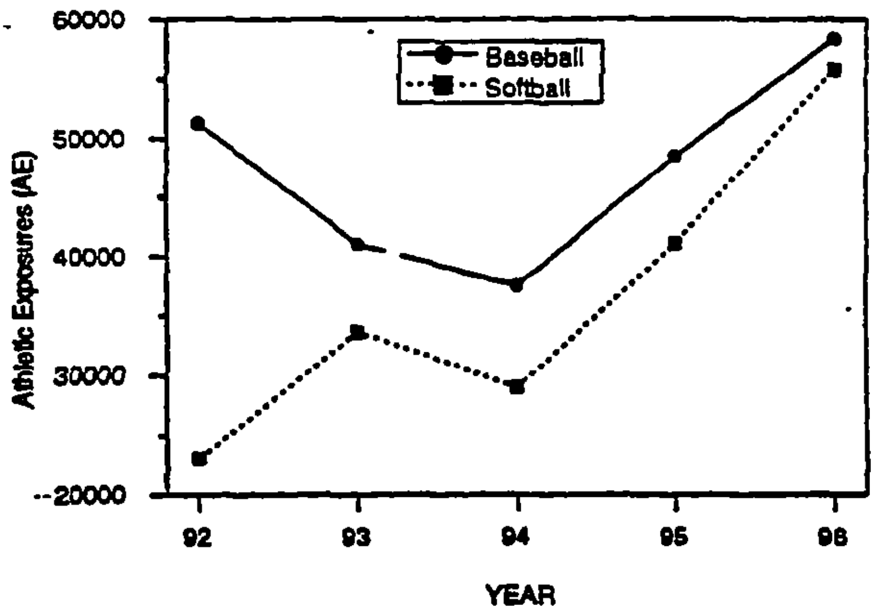


Figure 2. Number of Athletic Exposures (AE), defined in this analysis as one player per one game, for each year of the analysis. AE multiplied by injury rate gives number of injuries recorded in sample. Total expected injuries are then estimated by scaling to total number of schools.

Conclusion

The concern of safety is not substantiated by the available injury data. The total frequency of injuries from batted balls have remained constant in collegiate baseball from 1992 through 1996 (NCAA ISS, 1997). Similarly, injuries to the pitcher have also remained constant, with the frequency of these injuries for baseball and for softball being nearly identical.

Drawing conclusions from this data regarding injuries from the batted ball is limited for two reasons. First, because the majority of all bats used in this time period were alloy bats, a statistical comparison of injuries with wood bats is not possible. Second, the data are based upon a sampling of 14% and 18% of the baseball and softball programs, respectively.

Consistently, baseball and softball have one of the lowest *overall* injury rates of all collegiate sports since the NCAA ISS was developed in 1985.

AIM 2. To evaluate what time is necessary to avoid impact from a batted ball.

Introduction

A review of the available research literature on reaction time and movement time limitations was undertaken by Cassidy and Burton (Cassidy and Burton, 1997). Details of their review are provided in their manuscript in the Appendix.

Review and Conclusions

Their review suggested that the average collage or professional baseball player may be able to begin an accurate response only 125 ms after the ball is contacted and a player could complete a reasonable arm movement in at least 200 ms. The total response time from the contact of the batted ball was thus estimated to be 325 ms. This review was based upon limited scientific studies, and they strongly recommend that more ecologically valid experiments are need to verify their estimates.

The relationship between batted ball velocity and the time available for a player to react when he is located 55 ft from the batted ball is plotted below in Figure 3.

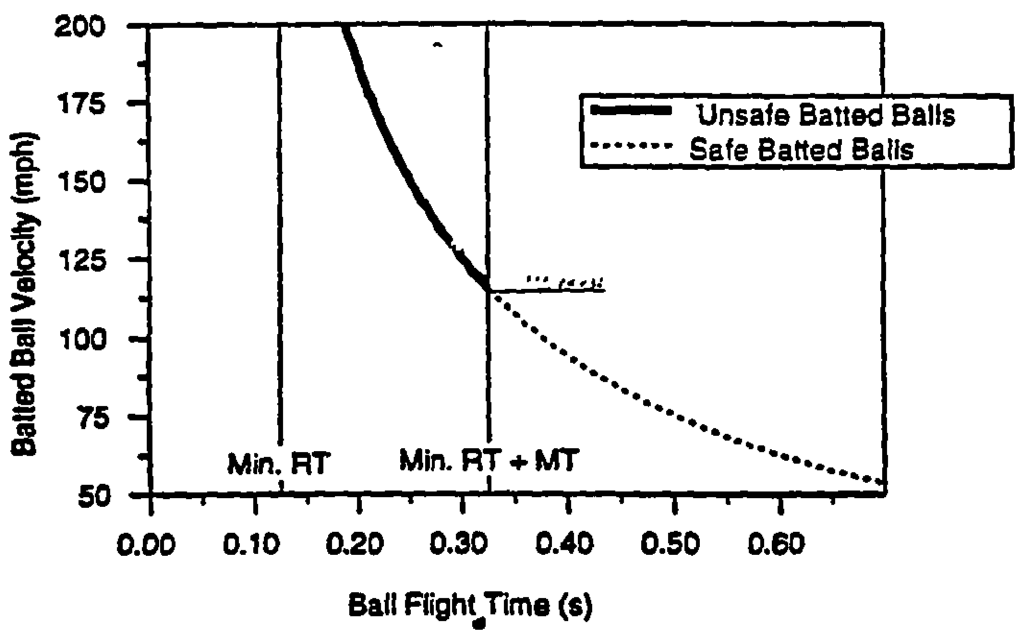


Figure 3. As the time the batted ball remains in flight decreases (i.e. the faster the batted ball velocity), the likelihood of being struck by the ball increases. The minimum time required for a subject to accurately react to a stimulus (minimum reaction time (Min. RT)) is estimated to be 0.125 seconds. An additional

0.200 seconds is the estimated time required to move an arm (minimum movement time (Min. MT)). Thus, it is estimated that a ball flight time of 0.325 seconds or more is required for a player to respond and to prevent injury from being struck by the ball. This flight time corresponds to a batted ball velocity of 115 mph. Further studies are required to verify these estimates. *Adapted from Cassidy and Burton, 1997.*

Injury Severity and Frequency Increase with Increases in Impact Velocity

Concerns that injuries will become more severe and more frequent as batted ball velocity increases are substantiated in part by numerous experiments on a broad range of impact injuries (e.g. Fung et al. 1988; Backaitias, 1993; Crisco et al., 1997). The findings of these experiments demonstrate that both the severity and frequency of injury increases as impact velocities increases. Therefore, given that injuries have occurred in baseball using wood bats, further increases in batted ball velocities would increase the probability of injury.

The research supporting the above statements is expansive, published in peer-reviewed journals, and will not be further discussed here. The interested reader is directed to the references cited above. Using these references an extensive literature search can also be readily mounted.

Standards for Injury Prevention

It is important to note that *all* standards related to the prevention of injury in sports are necessarily arbitrary. This does not imply that the standard was not based upon scientific information. Rather, a standard consists of an arbitrary level of acceptability for two reasons: the tolerance of a sampled population is at best normally distributed (i.e. the severity of an injury can differ from person to person) and secondly what risk of injury is acceptable also varies (i.e. a free (untethered) rock climber is accepting a risk of injury that would be not be acceptable for youth football, for example).

Football helmets are required to meet a standard that minimizes (you can never eliminate all injuries) the risk of severe brain injury (referred to as brain injury herein). Deceleration of the head is the injury criterion and is measured as the Gadd Severity Index. Impacts to the head that result in a low GSI (low head deceleration) have less of a risk of injury than do impacts with a high GSI. A mathematical formulation has been developed that relates the value of the GSI with the risk of injury (Figure 4). Existing standards require that football helmets reduce the impact to the head to a level of 1200 GSI. Note that this corresponds to a value of 16.22% of the population at risk of severe brain injury. Siimplisticly, helmets that test above this level are considered "unsafe", while those that test below this level are considered "safe" and pass the standard. According to the relationship presented in Figure 4, even if all helmets meet the 1200 GSI standard, there are still 16.22% of the population at risk of severe brain injury! What must be appreciated is that the specific choice of the value of 1200 was arbitrary, there is nothing magically scientific nor magically legal about the value of 16.22%. However, it is a realistic value that is practical, and most importantly, the injury data since the standard has been put into place have indicated that the standard has eliminated all but 1 or 2 injuries per year. Changing the standard to a level of, say 100 GSI, where we would expect a 0% risk of brain is not practical because no helmet could pass this standard level.

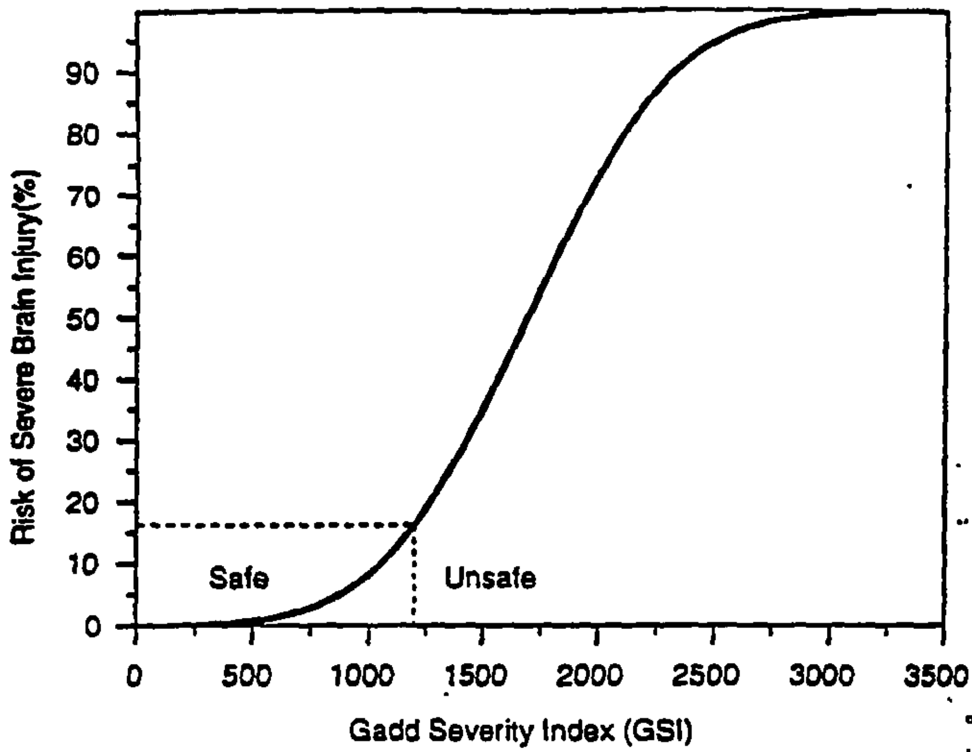


Figure 4. The standard requirement for all football helmets is the reduction of a defined impact to a level of 1200 GSI. The GSI is a measure of the deceleration of the skull for a given impact. Based upon extensive scientific data, the above relationship between the GSI and the percentage of the population at risk of severe brain injury was formulated. It is important to note that at a GSI level of 1200, below which helmets pass the standard and are considered safe, there is still a risk of severe injury to 16.22 % of the population. This is an arbitrary value, there is nothing magical about the value of 16.22%. Despite the arbitrariness of this value it is practical (helmets can be manufactured cost-effectively to meet it) and preventive based upon the available injury data (few severe injuries still do occur). Therefore, the standard is beneficial and the risk of injury, although it exists, is considered acceptable in the game of football.

It is possible to draw an analogy from the football helmet standard to baseball (softball) ball and bat performance. First, it can be postulated that Figure 4 also applies to the risk of injuries from the batted ball. One can assume that the bat-ball performance is measured by batted ball velocity and is analogous to the Gadd Severity Index in Figure 4. It can also be assumed that the risk of injury to the pitcher being contacted with the batted ball is analogous to the risk of severe brain injury in Figure 4. If the x-axis of Figure 4 is batted ball velocity and the y-axis is the risk of injury from the batted ball, then we see a continuum of risk. Further, it would impossible to set a risk of zero because injuries with wooden bats and traditional balls have been documented.

To emphasize the point again, science may be able to describe the relationship of the risk of injury from the batted ball, but since it is a continuum and injuries have already been documented with traditional equipment, science can not define the risk of injury. Only the people of baseball and softball can determine what risk is acceptable.

BALL-BAT PERFORMANCE

AIM 3. To evaluate existing testing methods for ball performance.

Introduction

The existing specification for ball performance (listed below) require that a ball's coefficient of restitution (COR) fall within a certain range when the ball is fired at 60 mph into a flat, rigid wall. COR is defined simply as the ratio of rebound velocity to inbound velocity.

Existing Baseball Ball Standards

The NCAA rule on baseballs is Rule 1-10. The baseball is a sphere weighing not less than 5 nor more than 5 1/4 ounces avoirdupois and measuring not less than 9 inches nor more than 9 1/2 inches in circumference. It shall be formed by yarn wound around a small core of rubber, cork or combination of both and covered by two pieces of white horsehide or cowhide tightly stitched together.

In addition to the above, the Official NCAA Championship baseball must have a coefficient of restitution (COR) with a minimum value of 0.525 and a maximum value of 0.555 at an initial velocity of 85 feet per second (26 m/s, 58 mph).

Existing Softball Ball Standards

The NCAA rule on softballs is Rule 3-1. The softball shall be an optic yellow sphere with raised red thread seams. It shall have a center core of polyurethane mixture, No.1 quality long fiber kapok, or a mixture of cork and rubber. The cover shall be smooth and made of chrome tanned, top grain horsehide or cowhide. It shall be affixed to the core by cement and sewn with waxed cotton or linen thread by the two-needle method with not fewer than 88 stitches per cover. The ball shall meet the following specifications: a diameter of at least 11 7/8 inches but not more than 12 1/8 inches; a minimum weight of 6 1/4 ounces but not more than 7 ounces; and a maximum COR (coefficient of restitution) of 0.50, but not less than 0.48.

Proposed Methodologies (Both Baseball and Softball)

Two proposed methods for estimating ball COR and ball stiffness are:

1. Test Method for Measuring the Coefficient of Restitution (COR) of Baseball and Softballs. Proposed, Subcommittee F08.26, ASTM, Revised March 25, 1996.
2. Test Method for Compression-displacement of Baseball and Softballs. Proposed, Subcommittee F08.26, ASTM, Revised March 25, 1996.

Review

While much of the game of baseball has been well studied scientifically (e.g. Adair, 1994; Watts and Bahill, 1990), measuring bat performance has been a much debated topic (e.g. Collier, 1992; Kirkpatrick, 1963; Bahill and Karnavas, 1989; Noble and Walker, 1993; Calder and Sandmeyer, 1997), and no report to date has rigorously studied the complexities of the ball-bat impact and bat performance. Ball performance has been studied somewhat more (Heald and Pass, 1994; Hendee et al., 1997).

While the advantage of the proposed (but widely adopted) standard test methodology is its cost effectiveness and practicality, it is most likely insufficient to estimate ball performance in the field. Albeit, the actual performance of a ball in field conditions has not yet been determined.

The major limitation of the existing methodology is the specification of a single unrealistic inbound velocity of 60 mph. This limitation is due to the fact that COR is dependent on inbound velocity. This fact was suggested by Adair (1994) and documented by Heald and Pass (1994). More recently Hendee et al., (1997) have documented with a wide range of baseball models an approximately linear decrease in COR with increase inbound velocity up to 90 mph (Figure 5). This work clearly demonstrates that several baseball models pass the existing standard at 60 mph but have significantly different COR values at 90 mph. It should be appreciated that while the work of Hendee et al. is the most extensive study that is publicly available to date, there remain numerous limitations to the methodology when extrapolating the results to actual field performance.

The limitations of measuring ball COR off a stationary wall with the proposed methodology include:
1) Inbound Velocity. Assuming a bat swing velocity of 70 mph and a pitch velocity of 80 mph, the relative approach velocity is then the sum, or 150 mph. The specified 60 mph measurement and the range of 60 to 90 mph employed by Hendee et al. (1997) are significantly less than actual field velocities.
2) Target Shape. The present target used in all of the available studies was flat in shape. What effect the cylindrical shape of the bat would have on COR is not known.
3) Ball Mass. In the field, the exit velocity of a lighter ball will be faster than a heavier ball, assuming all else is the same. This will be perceived as (and is) an increase in performance on the field. The increase in performance is due simply to the conservation of momentum. The influence of ball mass on performance cannot be addressed with any of the studies to date since the target is stationary.
4) Ball Stiffness. Stiffness as a measure of the ball's ability to deform is not directly related to ball COR. However, stiffness may play an indirect role by minimizing ball deformation which is presently not well understood. More importantly, stiffness should be monitored and controlled by specifications because it *may directly correlate with the likelihood of injury. This may have a much more notable role in softball* where tradition has not limited ball design.

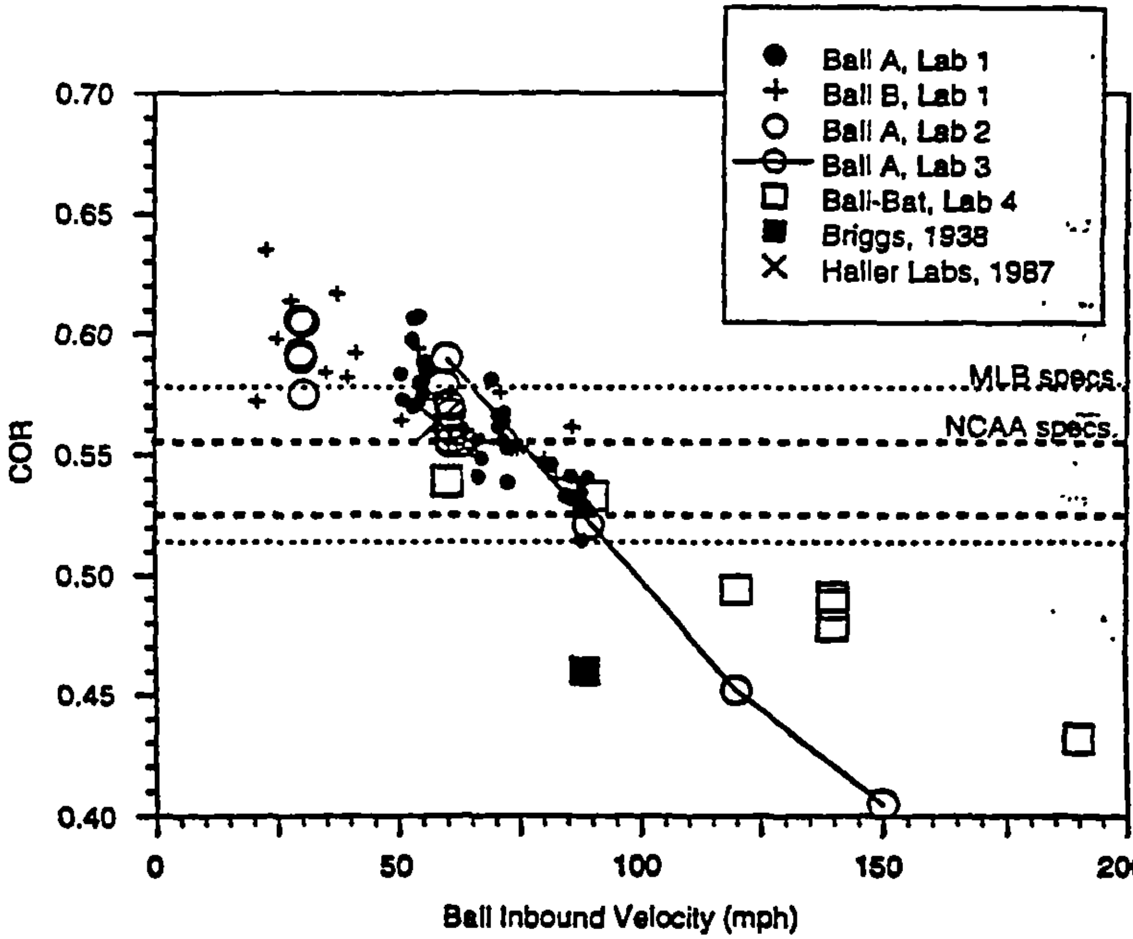


Figure 5. Baseball ball COR measurements against a flat, stationary target at various inbound velocities using ASTM methodology, but with multiple velocities, were performed at several labs (Lab 1, Lab 2, and Lab 3). Lab 4 employed the Baum Hitting Machine, which measures ball COR using a swinging bat and ball. In this graph bat velocity and ball velocity were equal and summed to give the inbound velocity, except at 140 mph (Fallon et al., 1997). The three stacked values at an inbound velocity of 140 mph are

measurements at 60-80 mph, 70-70 mph, and 80-60 mph (bat-ball), respectively, with the COR increasing with bat velocity. For comparison, the data point reported by Briggs in 1938 and by Haller Labs in 1987 are also plotted (note the data from Haller Labs is at approx. 60 mph and just above the NCAA specs.). If the data from Lab 4 can be compared with the other labs, one may speculate that the COR of a flat, stationary target under estimates the COR of a cylindrical, moving target.

Conclusions

Existing standard methodology is likely insufficient to predict the field performance of batted balls. The most likely test methodology able to predict filed performance is an apparatus that is capable of generating realistic bat and ball velocities. Prior to the development and adoption of such a device, several improvements in the existing standard, such as multiple inbound velocities could and should be readily adopted. (Note: Although the language translations are not completely clear, it appears that this is similar to what the Japanese governing bodies have adopted in their performance requirements). Stiffness measurement should be incorporated into the specifications.

AIM 4. To evaluate existing testing methods for measuring bat performance.

Introduction

In this Program, bat performance is defined as a measure of the maximum batted ball velocity. The purpose of this Aim was to evaluate existing laboratory test methodologies for predicting bat performance in the field. The existing standards that relate to bat performance are also listed below.

Existing Baseball Bat Standards

The NCAA rule on baseball bats is Rule 1-11. The components of that rule relative to this Research Program are: 1) The bat may not weigh, numerically, more than five units less than the length of the bat (e.g., a 35-inch-long bat cannot weigh less than 30 ounces). 2) Also required, but not in the NCAA rule book for 1997, is that a bat must not exceed a Bat Performance Factor (BPF) of 1.14 (plus or minus .01 for margin of error). The BPF is assumed to be determined using ASTM Standard Test Method For Measuring Bat Performance Factor (Revision 5.3).

Existing Softball Bat Standards

The NCAA rule on softball bats is Rule 3-2. The baseball bat shall be made of wood, metal, plastic, graphite, carbon, magnesium, fiberglass, ceramic or any other composite material approved by the American Softball Association (ASA). Any new composite construction bat must be reviewed and approved by the ASA. *Note: bats made of or containing TIMETAL 15-3 or TELEDYNE 15-333 titanium alloy shall not be used until further testing is completed.* The bat shall be round or three-sided and shall be smooth. If the barrel end has a knurled finish the maximum surface roughness is not more than 250 if measured by a profilometer or 4/1000 if measured by a spectrograph. The bat shall not be more than 34 inches long, nor exceed 38 ounces in weight. If round, the bat shall not be more than 2 1/4 inches in diameter at its largest part; and if three-sided, shall not exceed 2 1/4 inches on the hitting surface. A tolerance of 1/32 inch is permitted to allow for expansion on the round bat. *Note: If the bat ring goes over the bat, it should be considered a legal bat.* The bat shall have a safety grip of cork, tape (no smooth, plastic tape) or composition material. The safety grip shall not be less than 10 inches long and shall not exceed more than 15 inches from the small end of the bat. The bat shall be marked OFFICIAL SOFTBALL by the manufacturer.

Review

There exists much controversy over the factors influencing bat performance and the methods for measuring baseball bat performance. While the root of this controversy is undoubtedly seeded in the complexity of the swung bat-ball impact, the lack of published rigorous scientific studies is the major reason for this controversy. While the bat-ball interaction is defined by the laws of physics, the assumptions generally made are a necessary simplification and there exist few laws with which the biomechanical factors can be predicted. Thus scientific studies measuring bat performance are crucial to the development and validation of the various hypothesis about bat performance.

Although numerous individuals have developed a variety of methodologies for evaluating bat performance, there are *no* published documents describing a methodology for testing bat performance.

Another major limitation that must continually be emphasized is that at present there are no rigorous published studies measuring the actual field bat-ball impact with which to validate any of the laboratory tests.

Hence the following review, which is based upon data that was provided by various individuals and laboratories, can not and was not intended to review the validity of the results in predicting field performance. Rather, *the data are reviewed based upon repeatability, multiple lab variability, and the likelihood* of predicting actual bat performance in the field.

Two test methodologies for estimating bat performance were available for review. Each is described below.

Brandt/ASTM Method

The most generally accepted method for predicting bat performance was developed by R.A. Brandt, Ph.D. of New York University and subsequently adopted as a proposed standard test method for ASTM. This test methodology predicts bat performance by measuring bat-ball COR, defined as the product of ball COR and Bat Performance Factor (BPF), then uses this factor to calculate the batted ball velocity given a specified swing and pitch velocity.

The test procedures are well described in the document entitled "Standard Test Method for Measuring Bat Performance Factor, Proposed ASTM Standard (Revision 5.3, 9/12/95)." Two more recent modifications of this document include an increased ball inbound velocity (see References).

Unfortunately, despite the well described methodology, there appears to be no documentation of *the test variability nor any documentation on any goal driven study. The only relevant data that is publicly* available appears to be an unpublished preliminary report by Brandt (1995). The report describes a field test of several bats in which batted ball velocities were correlated with the laboratory measurements of the each bat's BPF. Unfortunately, the details of the methodology are not clear from this preliminary report and the data collection appears random. A statistical analysis was not presented.

There were three principal conclusions to this preliminary report, the last is agreement with the suggestions of this Research Program and *stated* "3) *Performance standards which preclude the use of* such lively bats and balls should be invoked and strictly enforced." While the invoking of a standard to preclude certain products is, in the opinion of this report, the responsibility of the people of baseball and softball, enforcing whatever is invoked is crucial. The second conclusion is a mystic explanation of the events that occurred during the College World Series (CWS) and does not warrant further discussion.

The primary conclusion was two fold: "1) The lab measurements have an excellent correlation with the field tests. The BPF, together with the weight, COM [center of mass], and MOI [moment of inertia] provides a complete performance characterization of the bat." The first part of this conclusion is only partially supported by the data, as the number of samples in this study was low and no statistical analysis was performed. The second part of this conclusion is in direct contrast to earlier findings in the report. The report states that ball COR, when increased from 0.54 to 0.58, has a much greater effect than increasing BPF factor from 1.13 to 1.15. Despite this acknowledgment of the importance of the COR the author states that the "BPF, ... provides a complete performance characterization of the bat" Yet it is well appreciated that ball COR is strongly influenced by the velocity, but this fact is not accounted for in this "complete performance characterization". This limitation is described in more detail below.

Since there were no baseball bat data available on the Brandt/ASTM, method this Program sought to collect data. In addition, since the major limitation of the existing method was an inbound velocity of 60 mph, data was also collected at elevated velocities in an attempt to eliminate this limitation.

One wood bat model and two C405 aluminum bat modes were randomly chosen. Both aluminum bat models had been previously tested by the Lab at NYU (Brandt) and certified as having a BPF of 1.14. Bats of the same bat model (not the identical bats) were tests using the Brandt/ASTM method at two facilities (Fluid Technologies Inc. and Hillerich & Bradsby, Inc.). The results were difficult to interpret (Table 1). Lab 1 reported results that were not consistent with the expected values of wood being slightly less than 1 BPF and the aluminum bats being greater with a value of 1.14 BPF. Lab 2 reported results that had a similar trend to those expected but required scaling to obtain the absolute BPF value previously measured at NYU.

Table 1. Average (n = 6 ball impacts) Bat Performance Factors (BPF) of wood and C405 alloy bats at 60 mph. Labs tested bats of same model, but not the identical bats. The reason for the range and variance in the BPF values is unknown. At Lab 1, two bats of each model were tested. At Lab 2, one bat of each model was tested. The actual measured BPF values at Lab 2 are given in parentheses and then these values were scaled to agree with prior measurement at the NYU laboratory.

Bat Model	Lab 1	Lab 2	Lab NYU
Wood	0.33 , 0.36	1.07 (0.647)	.
Alloy B	0.67, 0.86		1.14
Alloy C	-0.35, -0.37	1.14 (0.688)	1.14

A further effort was made to evaluate the Brandt/ASTM method by requesting additional testing at elevated ball inbound velocities. Three bat models had been previously tested at 60 mph at the NYU lab and each was found to have BPF value of 1.14. Bats of the same models were tested at Lab 1. While the absolute values were again not in agreement with the NYU measurements the results appeared more consistent. For each bat model, the BPF varied with inbound ball velocity, and each had a maximum BPF at 90 mph. These results were notably more consistent then previous results, but again the absolute values differed from those obtained at the NYU lab (Table 2).

Table 2. BPF (average, n = 6) of three non-wood bat models tested at elevated inbound ball velocities. Bats of the same model were tested at the NYU lab and were found to have a BPF of 1.14 at 60 mph.

	Ball Inbound Velocity (mph)			
Bat Model	60	90	120	140
Alloy D	0.85	1.13	0.76	0.91
Alloy E	0.83	1.2	1.09	0.86
Alloy F	0.97	1.22	1.07	0.89

Possible reasons for the discrepancy in the BPF values in Table 2 at 60 mph and those from the NYU lab include 1) Different bats of the same model were used and 2) slightly different procedures were employed. Assuming that manufacturing quality controls are high, it is unlikely that these different results can be attributed to differences in bat construction in the same model bats. It is more likely that slightly different procedures were used. However, if we assume that a simple linear scaling is possible between the res· :s of Lab 1 and the NYU Lab, we are s· ll presented with a BPF that is velocity dependent and appears to have a maximum at 90 mph.

An important procedure in determining the BPF factor is the value used for the ball COR. In all of the above data, the ball COR value used was obtained with the proposed ASTM methodology that employs an inbound velocity of 60 mph. It should be well appreciated that ball COR is velocity dependent, as illustrated in Aim 3, therefore in our continued efforts to evaluate the Brandt/ASTM method Lab 2 repeated the test at elevated ball velocities and determined the BPF using the ball COR measured separately at each of the inbound velocities (Table 3).

When the decrease in ball COR is taken into account, the results presented in Table 3 demonstrate that BPF remains dependent on ball inbound. The maximum BPF in these tests was at a ball inbound velocity of 90 or 120 mph.

Table 3. BPF (average, n = 6) of a wood and two non-wood bat models tested by Lab 2 at elevated inbound ball velocities. The ball COR used in the calculations of the BPF was determined separately at each inbound velocity (0.569, 0.511, 0.452, and 0.405). The values listed are the values scaled to the BPF value measured at 60 mph at the NYU Lab.

Bat Model	Ball Inbound Velocity (mph) 60	90	120	150
Wood	1.07	1.14	1.35	1.20
Alloy C	1.14	1.42	1.86	0.86
Composite A	1.00	1.11	0.88	0.87

Upon review of the above data, there are several important factors to keep in mind:
1) In my opinion, the data collected at Lab 1 and Lab 2 was done with the utmost diligence and honesty, and therefore poor lab technique is unlikely to be a source of the discrepancies.
2) Other than the values of 1.14 measured at 60 mph in the NYU Lab, there are no other data with which to compare the above results.
3) This Research Program has made an unprecedented attempt to evaluate all aspects of the Brandt/ASTM method. Further attempts to study and justify this approach should be carried out by those who support this test methodology.

Although BPF has been the most generally accepted value for quantifying bat performance, it is a factor that is somewhat non-intuitive. Batted ball velocity is more easily understood value. The Brandt/ASTM method does provide an approach for determining the batted ball velocity.

Estimating batted ball velocity by the Brandt/ASTM method requires values for: bat swing velocity, pitch velocity, bat weight, ball weight, bat moment of inertia about the pivot point, e = BPF times ball COR, distance from pivot point to center of mass, and center of percussion. The details of the definitions of these variables and the equations for calculating batted ball speed are provided in the document describing the proposed test methodology (ASTM, 1995).

There is an important incorrect statement in the standard test methodologies (ASTM, 1995). Section 8.3.6 states that *"One must choose a ball COR to determine the batted ball speed".* This is incorrect.

While ball COR is crucial to determining the BPF, it is mathematically canceled out when one calculates e as BPF times ball COR. In other words, the predicted batted ball speed using the Brandt/ASTM is completely independent of the ball COR. While this greatly simplifies the approach, it emphasizes the limitation of testing bat performance using an unrealistic relative velocity. It remains to be determined if this limitation can be addressed, but the data reported above suggests that this is unlikely. To this end, it should be noted that the Brandt methodology was developed for slow pitch softball and may not (and was not intended to) be applicable to baseball or to fast-pitch softball (Brandt, 1997).

The Baum Hitting Machine (BHM)

The Baum Hitting Machine (BHM) is a unique device capable of measuring batted ball velocity for any specified swing and pitch velocities. This is accomplished using two servomotors rotating in opposite directions. Presently, the BHM is a working prototype with patents pending, limiting accessibility. Similar to the Brandt/ASTM, there are no published documents presenting comparative data. The review of the BHM was further limited because unlike the Brandt/ASTM apparatus there is no document detailing methodology and only one apparatus presently exists.

With the assistance of Major League Baseball (MLB) a group of independent researchers were permitted to evaluate and document the BHM apparatus in detail. The evaluation included both component and system level analyses of the BHM hardware and test procedures. Their findings were recently reported in a final summary statement from which the following summary was extracted (Fallon et al., 1997).

Fallon et al (1997) concluded that the BHM is a state-of-the-art machine capable of accurately measuring ball exit velocity. The machine can simulate impacts at any specified combination of bat swing and pitch velocities up to 200 mph. Verification of the BHM test results was accomplished through their independent laboratory property measurements and computational impact modeling efforts at UMASS-Lowell. They concluded the accuracy of the BHM performance measurements was ± 1 mph using the calibrated results from 5 valid tests. The accuracy here was determined by evaluating the equipment specifications as well as analyzing the data with a 95% statistical confidence. Planned modifications to the equipment and process should improve the test accuracy by a factor of 3. The definition of accuracy refers to the repeatability of the measurements on the single appratus.

In comparing wood bats to aluminum bats, they found an approximately 3 to 4 mph increase in the raw batted velocities with the aluminum bats, where raw refers to the actual batted ball velocity. Because the servos are velocity controlled, they developed a formula called the RBP (Relative Bat Performance) to compare differences in exit speeds based on variations of bat weight, weight distribution, and length. When applied, the RBP predicts the difference in aluminum to wood bats increases to 8 mph off of similar wood bats.

An additional capability of the BHM is the ability to profile the bat. Profiling refers to examining the variations in exit ball velocity as a function of the location of the impact along the bat barrel. While the performance of all bats decrease as the impact moves away from the "sweet spot" toward the handle or towards the tip of the bat, aluminum bats were found to have a flatter profile as exit ball velocity decreased less than wood for the same change in location. In other words, the aluminum bats were found to possess an expanded "sweet spot".

The BHM can also be employed as the state-of-of-the-art machine for measuring ball performance. It eliminates the limitations of existing methodologies for measuring ball performance: realistic velocities are attainable and the target is a moving cylinder. Results detailing the use of the BHM in measuring ball performance were not reported bat Fallon et al. (1997).

Variability from facility to facility could not be evaluated because at present only one apparatus exists.

While the BHM is the most sophisticated apparatus for studying bat-ball impacts, its practicality as a standard test methodology remains to be demonstrated.

Comparison of ASTM/Brandt Method to the BHM Method

The lack of published data (in any format) makes comparison of these two methodologies difficult. However, a limited comparison is possible. The performance of two bats were considered: one wood and one C405 aluminum. Their physical properties are listed in Table 4.

Baum Hitting Machine (BHM). The two bats were tested using the BHM methods and the data were collected by Fallon et al. (1997). Each bat was tested with three protocols of bat and ball velocity: 60+80 mph, 70+70 mph, and 80+60 mph. The actual batted ball velocities for each of these protocols were measured.

ASTM/Brandt (NYU). There were no actual data available to this program. However, based upon previous presentations of data by Brandt and others, it was *assumed* that the BPF values for wood and C405 aluminum were 0.9 and 1.14, respectively. Note that the 1.14 should be a valid assumption since all NCAA baseball bats can not exceed this value. Given these BPF values, the physical properties of the bat, and the bat swing and ball pitch velocities, the batted ball velocities were calulated using the equations provide in the ASTM (1995) document.

Table 4. Physical properties of one wood bat and one aluminum C405 bat.

	Weight (oz.)	Length (in.)	CG (in.)	I about CG (oz-in^2)
Wood	33.2	32.9	11.85	3325
C405	29	34	12.95	3534

Note: 1 lbf-ft-s^2 = 1.356 kg-m^2 = 74130 oz-in^2

Results

The batted ball velocities measured using the BHM increased almost linearly with increasing bat velocity, while ball velocity decreased similarly so that the total relative velocity was constant for the three test protocols (Figure 6). The BHM documented a greater performance for the aluminum bat with batted ball velocities being 2.3%, 2.0%, and 1% greater than those measured by wood. Using the proposed RBP (Relative Bat Performance) described above by Fallon et al. (1997) the difference at 70+70 mph between wood and C405 was 7.3%. Note the standard devitions are not graphed, they are reported to be less than 1 mph (Fallon et al., 1997).

The predictions of the NYU lab were ideally linear, based upon the equations. A 10 mph increase in bat velocity generated a 10 mph increase in batted ball velocity, when the total velocity was constant at 140 mph.

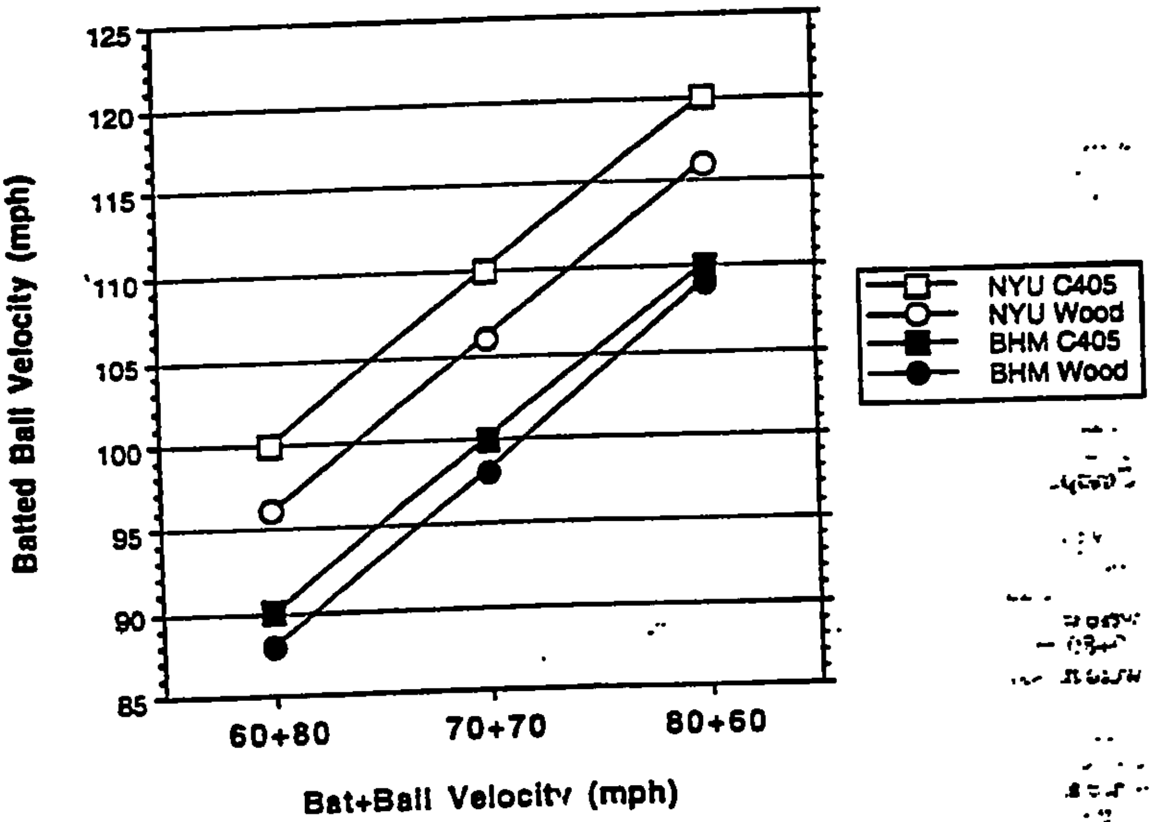


Figure 6. ***RawData*** from the BHM compared to ***theoretical*** predictions from the NYU lab assuming BPF of 0.9 and 1.1.4 for a wood and C405 aluminum bat. The approximate linear increase in batted ball speed measured with the BHM is in agreement with the theoretical predictions. The NYU predictions are limited mainly because the ball-bat COR is measured at 60 mph and then this same value is used to predict batted ball velocities at the higher, more realistic bat and pitch velocities.

Discussion

Predicting bat performance is complicated by the numerous factors that influence the batted ball velocity. Some of the factors that are not simulated in any of the existing methodologies are the biomechanical factors, of which two are probably the most significant. The effect of bat weight and inertia (weight distribution) on a players swing velocity and swing mechanics are not simulated in any of the test methods for bat performance (See Aim 5). The second limitation of existing methodologies is that the bats are rotated about a fixed point located at the handle grip, where as the motion of the bat in an actual swing is quite complex. We have illustrated the difference of the bat motion in the two precision renderings on the cover of this report. One figure is a rendering of the bat as it rotates about a fixed axis, as in the existing test methodologies. The other figure is a rendering of the bat during a players actual swing (Fleisig et al., 1997). Clearly these different motions have a different effect on the bending of the bat prior to and at impact. Although these limitations have been recognized it remains to be determined if they would significantly affect the predicted bat performance.

To address this, it is clear that a rigorous scientific study to measure bat performance in the field is needed. Such data would serve as the "gold standard" for which test methodologies could be compared. (We note that no cost effective, practical standard test methodology is likely to be a true simulation of the actual field event. But, it is crucial to understand *how* the test methodologies differ from the actual event.)

Conclusions

Methods for predicting bat performance are limited and remain to be thoroughly validated.

While the Brandt/ASTM has gained wide acceptance, there is limited documentation and its ability to simulate impact at the higher velocities of baseball and fast-pitch softball remain questionable. The most severe limitation of this method is that ball-bat COR is measured at 60 mph. Batted ball velocities at higher realistic velocities (e.g. 150 mph) are predicted using the ball-bat COR measurement at 60 mph. It should be noted that the Brandt methodology was developed for slow pitch softball and may not (and was not intended to) be applicable to baseball or to fast-pitch softball (Brandt, 1997).

The working prototype of the BHM is well suited for evaluating both bat and ball performance at the elevated impact velocities of interest here. The clear advantage of the BHM method is the ability to measure ball-bat COR at specified combination of velocities.

AIM 5. To determine the effects of bat mass and inertia on swing velocity.

Introduction

Increases in swing speed increase batted ball velocities. This observation is often considered the motivation behind a strength training program for batters and the use of "lighter" bats, since it is generally accepted that "lighter" bats can be swung faster than "heavier" bats. Simple extrapolation suggests that a feather-light bat can be swung the fastest, however, a feather-light bat swung at high velocities may not result in the highest batted ball velocities (Here we are neglecting the practicality of manufacturing and the durability of a featherlight bat). Bahill and Karnavas (1989) have suggested that there is an ideal bat weight which maximizes the batted ball velocity. This suggestion is based upon the incorporation of both the physics of bat-collision and physiology of the muscle force-velocity relationship. The effect of the ideal bat weight on actual batted ball velocities remains to be measured. One limitation of this work is that the ball-bat collision analysis assumes the motion of the bat is pure translational or linear. Under the assumption of linear motion only the weight or mass of the bat is a factor.

Consider two bats of the same weight (mass). One bat is handle-heavy, while the other bat is barrel-heavy. Under the assumption of linear motion there is no difference in the expected swing velocities. However, the motion of the bat during an actual swing contains both translational and rotational motion. Therefore, the handle heavy-heavy bat can be swung faster because more of the weight is located closer to the body. Heaviness of a bat is specified by it mass, and the distribution of the mass along the length the bat is specified by the mass moment of inertia (inertia) of the bat. The inertia of the bat describes its resistance to an applied torque. It is important to note the inertia is a minimum when the bat is rotating about the bats center of gravity and the inertia increases as the rotation axis moves further away from the bats center of gravity.

To further examine the relationships between swing velocity and bat mass and inertia, two studies were undertaken. Each study documented the effects of varying bat mass and inertia on swing velocity in groups of collegiate baseball players and softball players. One study was performed at Mississippi State University (MSU) under the direction of Keith Koenig, Ph.D. and the other study was performed at the American Sports Medicine Institute (ASMI) under the direction of Glenn Fleisig, Ph.D. The final reports of each study with baseball players are provided in the Appendix. The reports on the studies with softball players are in preparation.

Review

The details of the methods used in each study are supplied in the respective final reports (Fleisig et al., 1997; Koenig et al., 1997) and will not be described here.

In brief (extracted from the joint abstract by Fleisig and Koeing (1997) entitled Inertial Effects on Baseball bat Swing Speed), the design of the experiments was based upon the hypothesis that although *length-weight unit difference is the bat property which is presently restricted by the NCCA Rules, it is the* bat moment of inertia which has the dominant effect on swing velocity. In these studies, the bat inertia was determined about a representative point in the batter's body and defined as being located 20 inches inward from the handle. Bats used in a previous study at MSU (1989) (see Koeing et al., 1997 for full reference) and in both present studies were compared by plotting their length-weight unit difference (length (in.) - weight (oz.)) versus their moment of inertia (Figure 7). While there was a general correlation between unit difference and bat inertia, the relationship was not highly linear suggesting that unit differential and inertia were only roughly related.

Since bat swing motion is both translational and rotational, the speed of the bat depends upon the point at which the bat speed measurement is taken. In the three studies (MSU, 1989; Koeing et al., 1997; Fleisig et al., 1997), bat swing speed (also refereed to as velocity) was measured at different locations on the bat and at different locations of the plate. The two MSU defined the location relative to the plate. The ASMI data defined the location relative to the contact point on the bat. Despite these differences the general results agree relatively well (Figure 8). From Figure 8 it can be concluded that bat inertia about a body axis has a better correlation with bat speed than does bat length-weight unit difference. As expected, all three studies showed that bat speed increased as bat moment of inertia decreased. Within the range of bats studied, the correlation between speed and inertia was assumed to be linear. Based upon this assumption of linearity each study was able approximate a direct relation between bat speed and bat moment of inertia. Koenig et al. (1997) predict that the difference in bat speed is approximated by

$$\Delta V = -\frac{4\left(I_1^B - I_2^B\right)}{0.1},$$

where ΔV is the change in bat speed (mph), and I_1^B and I_2^B are the moment of inertia for bats 1 and 2 about the body axis in units of lbf-ft-s^2. The axis was defined as being located 20 in. inward from the handle. Fleisig et al. (1997) predict that the bat speed is given by

$$V = 69.6 - 48.7\, I^H,$$

where V is the bat velocity (mph) and I^H is the bat moment of inertia about the bat's handle in units of lbf-ft-s^2.

In an attempt to examine more fully the above predictions, we compared the calculated differences between two bats, one (heavy) wood and one aluminum with the physical properties listed in Table 5.

Table 5. Physical properties of one wood bat (Bat 1) and one aluminum bat (Bat 2).

	Weight (oz.)	Length (in.)	CG from handle (in.)	I about CG (lbf-ft-s^2)	I about handle (lbf-ft-s^2)	I about body axis (lbf-ft-s^2)
Bat 1	33.2	32.9	20.9	0.0410	0.2095	0.6864
Bat 2	28.6	34	22.2	0.0449	0.2646	0.8406

Note: 1 lbf-ft-s^2 = 1.356 kg-m^2 = 74130 oz-in^2

Given the above, the difference in swing speeds between the wood and aluminum bat is predicted to be 2.7 mph by the Fleisig method and 6.2 mph by the Koenig method.

The limitations of these studies include the following. Only bat swing velocities were measured. The actual effects on batted ball velocity were not determined. The players participated in this study during a single session so the effects of learning and compensating for the differences in bats could not be studied. The effects on swing mechanics and motion patterns were also not studied.

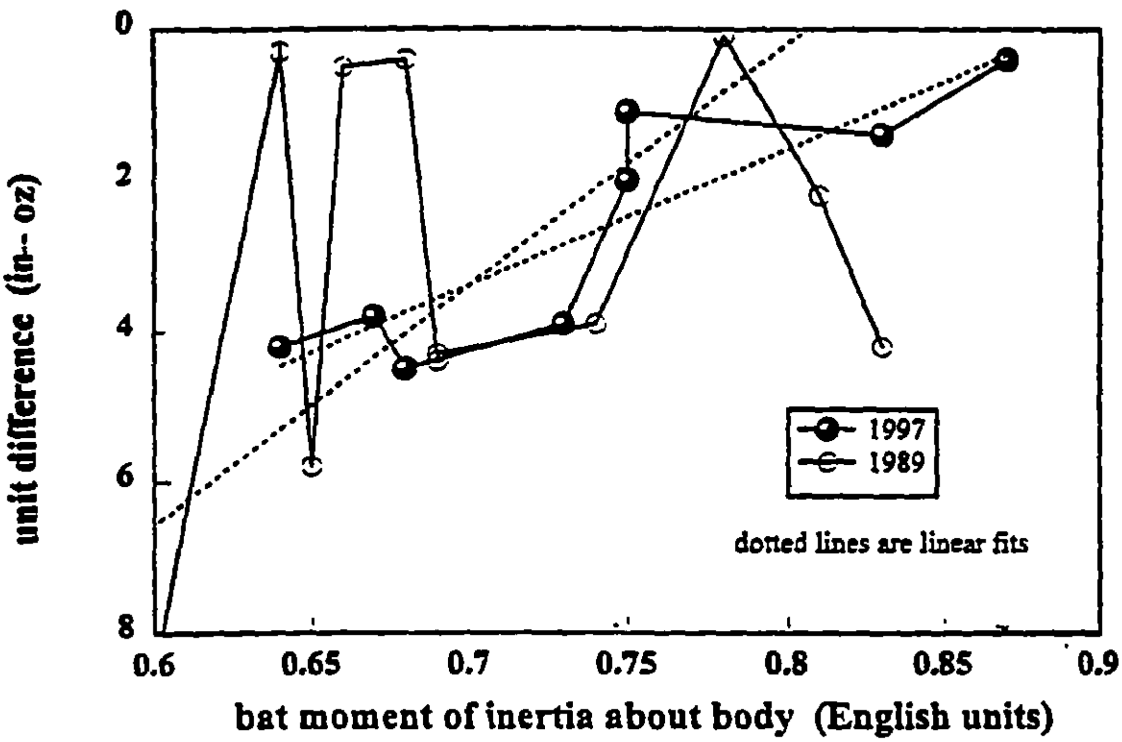
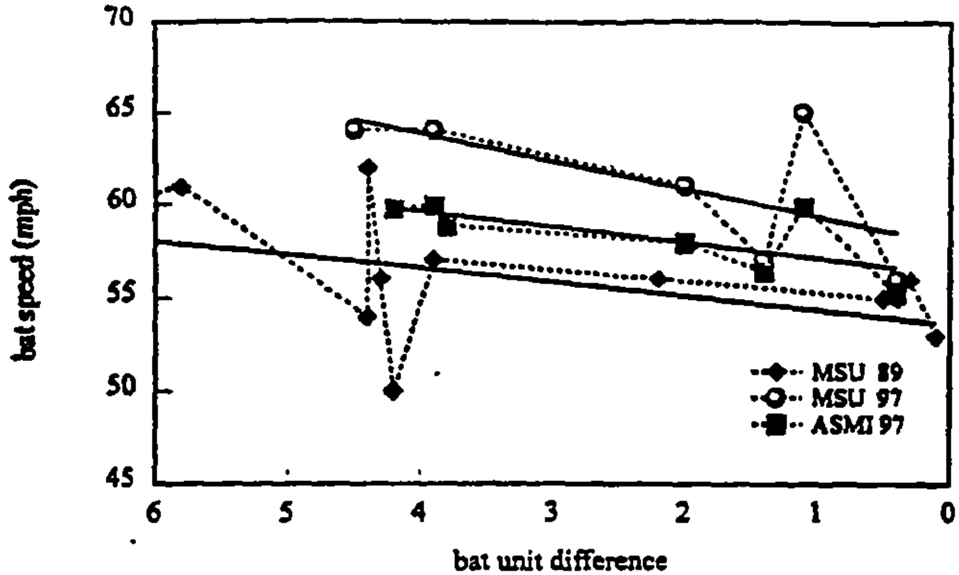


Figure 7. The length-weight unit difference (length (in.) minus weight (oz.)) of various baseball bats did not correlate well with the mass moment of inertia (lbf-ft-s^2). *Koeing et al., 1997 and Fleisig et al., 1997.*



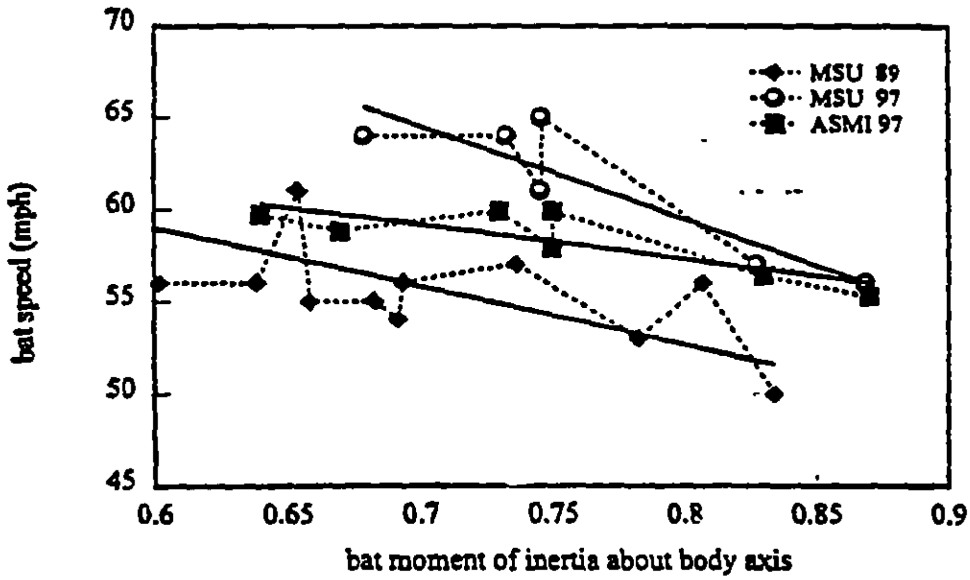


Figure 8. Bat speed had a stronger correlation with bat moment of inertia about the body axis (lbf-ft-s^2) than with length-weight unit difference (length (in.) minus weight (oz.)) for all three studies. *Koeing et al.,1989,1997 and Fleisig et al., 1997.*

Conclusions

Bat swing velocity decreases in a manner more closely related to the mass moment of inertia of the bat than to the weight of the bat. The bat swing is a complex motion containg both translation and rotation in three-dimensional space (see cover figure). Therefofe, comparison of swing velocity measurements is not trivial. The estimated difference in swing velocity between a heavy wood bat and an aluminum bat ranged from 2.7 mph to 6.2 mph in the studies reported here.

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RESPONSE TIMES FOR HIGH-SPEED BALL DEFLECTIONS IN BASEBALL AND SOFTBALL

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October 19, 1998

THIRD DRAFT

PLAINTIFF'S EXHIBIT
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1. INTRODUCTION

This paper reports the results of a preliminary determination of safe response times and hit ball speeds for a number of baseball and softball venues. This determination was based on tests in which balls were randomly shot with measured speeds towards subjects standing a measured distance away behind a protective net. The subjects were instructed to attempt to deflect the incident ball with a glove before being hit. The result of each attempted deflection (success or failure) was recorded for each shot. (Attempted deflections from pitching positions or by dodging motions were also recorded.) A total of 31 male and female subjects from various categories (college, high school, recreational, senior, and youth baseball and softball) were tested, and the results of over 2000 shots were recorded.

The tests were run during the course of a four days at the H&B indoor testing facility in Texas in August 1995, but, because the necessary funding was unavailable, the data were not tabulated or analyzed until August 1998. During the three years between the tests and the analysis reported here, player safety has become of increasing concern because of the use of high-performance balls and bats, in spite of the fact that baseball and softball remain among the safest of sports and there has been no increase in injuries from hit balls during the past five years.

The results reported here are preliminary. They suggest reliable first estimates of safe response times and hit ball speeds in the college baseball, senior softball, and women's high school softball venues, for which there were sufficient data to insure reasonable statistical significance, but more data is needed in the youth, high-school, and recreational baseball venues, as well as in the men's B-level and senior softball and women's college venues.

For a given measured projected ball speed v and subject distance d, the time of flight between the cannon and the subject is not simply the ratio d/v because of the presence of air resistance. It is crucial to incorporate the effects of this air resistance because these effects are of the same order of magnitude as the difference in flight times arising from hits off of high-performance and low-performance bats. For example, for a baseball hit at v=100 mph = 147 fps, the actual time taken to travel a distance d=55 ft is 0.396 sec, whereas the naïve time d/v is only 0.374 sec, which is 6% less. The is the same percentage difference in the hit speeds off of a high-performance (BPF=1.15) and a low-performance (BPF=1.05) bat. (For 70-mph pitch and bat speeds and a ball COR of 0.54, the high-performance hit speed is 104.6 mph and the low-performance hit speed is 98.8 mph. See Reference 1 for definitions of BPF and COR.) Air resistance has an even greater effect in softball. It takes 0.404 sec for a typical softball hit at 100 mph to travel 55 ft.

The flight time for each shot was therefore evaluated from the measured ball speed and flight distance using the well-known effect of air-drag. These evaluations are based on the trajectory equations given in Appendix 1. As many shots as time and fatigue-avoidance permitted were made for various distances and speeds, and the result (hit or miss) was recorded. These data were then used to determine which flight times are safe and which are unsafe for each category.

The goal is to determine from these results reliable estimates of the maximum safe flight time in each category. The maximum safe hit-ball speed can then be calculated, again taking air resistance into account. To proceed, it must be decided what is an acceptable level of injuries arising from hit balls. For example, virtually no injuries will result from a flight time of 0.50 sec, but a game with such a large travel time between a hitter and a pitcher would require such dead bats that far too few hits would occur. On the other hand, a flight time of 0.23 sec would result in far too many injuries. (Elite college baseball pitchers would be hit 50% of the times a ball was directed at them in this case.) It is not the purpose of this report to recommend an acceptable injury level and so the question of what is a safe maximum flight time will not be fully answered here. More data in the neighborhood of 0.4-sec flight times is necessary, as well as information on how often a hit ball is actually directed towards a pitcher.

It is, however, possible to make reliable first estimates of safe maximum times and speeds based on the present data and reasonable extrapolations thereof. This will be done in Sec. 5. For college baseball players, the maximum flight time for which a subject was hit was 0.368 sec, the proposed maximum safe flight time is 0.38 sec, and the maximum safe hit–ball speed is 104 mph.

One interesting and unanticipated result of these tests should be mentioned here. For the game venues for which sufficient data exists, the graphs of deflection failure percentage verses flight time have been plotted and found to be very well fit by straight lines. This observed regularity ~~is useful for extrapolating the existing data, and its significance should be explored in the future.~~

In extrapolating the test results reported here to real game situations, important differences should be kept in mind. The test subjects were always concentrating on the task, always alert, and were required to perform a single anticipated response. These facts tend to lower response times since ballgame players can loose concentration, become distracted, and have to worry about various responses such as fielding. On the other hand, the test subjects did not have the opportunity to observe a hitter swing a bat before a ball was projected towards them, and this obviously tends to increase the response times observed in the tests. To the extent that these and other differences cancel out or are unimportant, the test and game situations can be directly compared.

If, for a given shot, the subject's response time is less than the ball's flight time, the ball is deflected and the response is a success, whereas if the response time is more than the flight time, the subject is hit and the response is a failure. The response time here is actually the sum of three separate times: viewing time, reaction time, and movement time. The viewing time is the time during which the subject observes the approaching ball before he decides what to do. The reaction time is the time between the subject's decision to respond and the initiation of his responding motion. The movement time is the time taken for the subject to move his glove to the position where it can deflect the ball. As mentioned above, there is present in an actual game a fourth time (anticipation time), during which the pitcher observes the motion of the hitter before the ball is hit. The existence of this anticipation time reduces the necessary viewing time. There is also evidence that the reaction time tends to shorten as the hit-ball speed increases, but the movement time tends to remain constant. See, for example, Reference 2.

Although the determination of safe response times is of paramount importance in addressing baseball and softball safety concerns, I am unaware of previous realistic attempts to accurately measure this quantity.

The following sections execute the program outlined above. The test protocol and subject demographics are given in Section 2. The test results are summarized in Section 3, analyzed in Section 4, and expressed in terms of hit ball speeds in Section 5. The conclusions are discussed and suggestions for further research are given in Section 6. The air drag equations are given in Appendix 1, the bat performance equations are given in Appendix 2, and the complete test data are given in Appendix 3.

2. PROCEEDURES

The tests were carried out at the H&B indoor test facility in Mt. Pleasant, Texas. A Jugs pitching machine (cannon) was used to propel baseballs or softballs towards the subject. The cannon was randomly re-aimed for each shot. The exit ball speed was set on the cannon for each data set, mainly between 90 and 100 mph, but the cannon itself provided random variations in this speed of about $\pm$ 5 mph. The precise value of the exit speed for each shot was measured and recorded using an Euler projectile speedometer. The cannon was shielded from the subjects so that the precise aim or time of firing could not be observed. The subjects were placed behind a protective net, which allowed them to freely attempt to deflect the incident balls, but which prevented these balls from hitting them. The subjects were given between five and ten practice shots before data were taken. The distances between the cannon and the subject were fixed at 15, 20, 30, 40,or 50 ft. I, at least one college baseball player, and usually other personnel observed each shot. If these observers agreed on whether or not the subject was successful in deflecting the ball, the result (hit or miss) was recorded, but if there was disagreement, the shot was repeated. In addition, each shot was taped by a video camera situated behind the cannon and aimed directly towards the subject. These tapes were all reviewed in slow motion to confirm the result of each shot.

For each shot, the following information was thus recorded: subject name and venue, distance from cannon, exit ball speed, and deflection success or failure. Over 2000 shots were recorded on 31 different subjects. The complete list of subjects and demographics (game category, sex, age, height, weight, and years of experience) is given in Table 1.

TABLE 1

CATEGORY	SEX	SUBJECT	AGE	HEIGHT	WEIGHT	EXPERIENCE
College Baseball	M	tm	22	5'10"	160	15
		tc	18	6'1"	180	10
		ls	20	6'0"	230	14
		lc	18	6'1"	195	11
		da	18	5'10"	168	11
		cz	22	6'0"	185	15
		bt	20	6'3"	190	13
		tb	19	5'10"	145	11
High School Baseball	M	ws	17	6'4"	180	10
		bm	17	5'8"	150	10
Recreational Baseball	M	mr	20	5'5"	128	6
		tc	30	6'6"	225	20
		rn	33	6'2"	235	10
		jm	54	5'8"	158	30
Dixie Youth Baseball	M	cm	11	4'9"	80	6
B-Level Softball	M	cd	24	6'4"	230	19
		ln	19	6'1"	196	15
Senior Softball	M	rh	39	6'5"	275	8
		da	42	6'3"	200	
		mc	44	5'5"	175	16
		jm	54			
		rn	33	6'2"	235	10
		mr	40			6
Girls (Dixie WS) SB	F	mp	14	5'6"	125	9
		mh	13	5'5"	120	8
High School Softball	F	jg	16	5'2"	130	10
		nz	16			11
		as	16			11
		lc	16			11
		tr	15			10
College (NTCC) SB	F	fm	18	5'7"	155	10

In addition to the above deflection tests from a standing position, a number of tests were run in which the subject executed a pitching motion before the ball was shot. The subjects were instructed to pitch an imaginary ball towards the cannon, and about 0.4 sec later (a typical fastball flight time from pitcher to hitter) a ball was shot back at the subject. These tests were performed in order to confirm that such pitching motions did not increase the response time necessary to avoid being hit by the return ball. Tests were also run in which the subjects were instructed to avoid being hit by attempting to dodge out of the ball's way. Such motions were seen to require larger response times.

From the exit ball speed and flight distance recorded for each shot, the ball's time of flight was evaluated taking into account the effect of air resistance. The deflection success rate was thus determined for a range of flight times from 0.10 sec to 0.45 sec. These data were then used to estimate the response times and hit-ball speeds necessary for safe play in each of the game categories.

3. RESULTS

After the ball exit speeds and flight distances were converted to flight times, a table of times and outcomes (success or failure) was obtained for each subject in each category. The data for all the subjects in each category were then combined and sorted according to increasing times. The results are given in Appendix 3, where all the calculated times are listed in columns and the corresponding outcomes (1 for failure or 0 for success) are given in the same row in the next column to the right. In order to interpret this data, the outcomes must be combined for specified, relatively small, time ranges. The data, in fact, fall naturally into four separate time ranges corresponding to the four main chosen distances of 20, 30, 40, and 50 ft. For those categories in which sufficient data existed, each of these time ranges was further divided into two separate ranges, giving a total of eight ranges.

Consider first the data for men's college baseball. The subjects were eight excellent players from various colleges. Their demographics are given in Table 1. The initial round of tests consisted of ten shots at each of the four distances for each subject, for a total of 320 shots. The combined data were divided into eight time ranges, two for each distance, and the results are given in Table 2. Each row in the table corresponds to a time range which starts at the time given (in ms) in the first column and ends at the time given in the second column. The averages of these two times are given in the third column. The fourth column gives the number of hits (failures), and the fifth column gives the total number of shots in each time range. The final column gives the percentage of shots that resulted in hits.

The increase in hit percent with decreasing flight time is clearly seen. There were no hits in the first range with the average time of 0.39 sec, whereas the subjects were hit nearly 50% of the time when the average time was 0.23 sec, and nearly 77% of the time when the average time was 0.14 sec. These results will be exhibited more clearly in a graph given in Section 4.

TABLE 2: COLLEGE BASEBALL SUMMARY

min time	max time	ave time	hits	shots	hit percent
376	398	387	0	36	0.0
363	373	368	4	44	9.1
297	318	307.5	8	35	22.9
279	295	287	13	45	28.9
221	236	228.5	17	35	48.6
209	219	214	27	45	60.0
145	153	149	27	37	73.0
135	144	139.5	33	43	76.7
HIGH SCHOOL WOMEN SOFTBALL SUMMARY					
389	433	411	6	58	10.3
360	386	373	13	62	21.0
307	336	321.5	13	48	27.1
290	305	297.5	18	52	34.6
224	245	234.5	28	61	45.9
190	222	206	30	59	50.8
149	167	158	37	53	69.8
141	148	144.5	42	47	89.4

The data for women's high-school softball are also given in Table 2. The subjects were five excellent players who played on the 1995 NET Sluggers team. Their demographics are also given in Table 1. There were 440 recorded shots in the initial round of tests. The results are similar to those for college baseball, but the hit percentage is significantly higher in each time range. There was about a 10% failure rate for a flight time 0.41 sec, 51% for 0.21 sec, and 90% for 0.14 sec. The time range for which no hits occurred was from 0.405 to 0.433 sec.

The data from the other subject categories are given in Table 3. The results for the two high school and four recreational baseball players are grouped into four time ranges, and the same trends as noted above are observed. Only one (11-year-old) Dixie Youth player participated in the tests, and, for safety concerns, data was only taken for him at 40 and 50 ft. His response times are clearly much greater than those above, but the statistics here are unfortunately limited.

TABLE 3: OTHER MENS BASEBALL DATA SUMMARY						
CATEGORY	min. time	max. time	ave. time	hits	shots	hit percent
High School	373	390	381.5	9	30	30.0
	293	325	309	8	20	40.0
	215	227	221	15	20	75.0
	140	148	144	18	20	90.0
Recreational	358	405	381.5	14	40	35.0
	281	315	298	21	40	52.5
	206	232	219	41	54	75.9
	140	156	148	15	20	75.0
Dixie Youth	401	424	412.5	12	20	60.0
	313	336	324.5	13	20	65.0

OTHER SOFTBALL DATA SUMMARY						
CATEGORY	min time	max. time	ave. time	hits	shots	hit percent
Coll BB play.	392	455	423.5	0	40	0.0
	305	344	324.5	1	40	2.5
	228	250	239	10	40	25.0
	149	165	157	15	40	37.5
	109	125	117	21	40	52.5
Coll Women	368	407	387.5	4	10	40.0
	288	318	303	4	10	40.0
	216	241	228.5	7	10	70.0
	139	156	147.5	10	10	100.0
B-level Men	353	429	391	2	20	10.0
	288	333	310.5	2	20	10.0
	213	250	231.5	14	20	70.0
	135	162	148.5	14	20	70.0
	103	120	111.5	14	20	70.0
Girls (DWS)	404	440	422	2	20	10.0
	423	341	382	4	20	20.0
	235	254	244.5	7	20	35.0
	151	163	157	8	20	40.0
Senior Men	373	440	406.5	19	60	31.7
	294	341	317.5	25	60	41.7
	219	254	236.5	28	60	46.7
	143	169	156	29	50	58.0

The remaining categories in Table 3 refer to shots with softballs. The results are grouped into four or five time ranges, depending on whether on not data were also taken at 15 ft. The subjects consisted of four of the college baseball players, two B-level men, one college woman, two girls, and six senior men. The trends are as before, but, because there is much less data, the results are, of course, not as statistically significant. Some noteworthy features of these results are the better performance of the college baseball players at deflecting softballs instead of baseballs, and the good performance of the two (13 and 14 year old) girls.

From the point of view of player safety, a most important number obtained in these tests is the maximum time for which a failure occurred (MAX HIT TIME). These times are given in Table 4 in increasing order. The number of subjects tested (SAMPLE), age range, and number of shots recorded is also given for each category of baseball and softball. All of these results will be analyzed in the following section, but it is immediately clear form these trends that response times vary considerably from category to category, and so the high-performance bats and balls that may be safe for college players may not be safe for younger or older players.

TABLE 4: CATCH TEST SUMMARY sec

CATEGORY	SAMPLE	AGES	SHOTS	MAX HIT TIME
College BB	8	18-22	320	0.368
High School BB	2	17	94	0.381
Recr BB	4	20-54	154	0.387
Youth BB	1	11	40	0.417
Coll men SB	4	18-22	200	0.331
Coll. women SB	1	18	40	0.373
B-level men SB	2	19,24	100	0.395
H.S. women SB	5	15-16	440	0.404
Girls (DWS) SB	2	13,14	80	0.413
Senior men SB	6	39-54	230	0.413

Additional tests, as described above, were performed on some of the college baseball players. The first issue addressed was whether or not a pitcher is in more danger of being hit by a batted ball than a player who is standing still before the ball is hit. Tests were performed at 40 and 50 ft on the three college players who had pitching experience. Ten shots at each distance and at each pitcher were recorded, and the result is that there was no observed increase in the response time needed to deflect the incident balls. Specifically, in both the 0.283-0.315 sec and 0.365-0.405 sec flight time ranges, there were 2 failures out of 30 shots; a 7% failure rate. There were no failures in the 0.370-0.405 sec time range, and the maximum time for which a failure occurred was 0.368 sec, exactly as in the standing tests. It seems safe to conclude, even with these limited statistics, that the pitchers do not require longer response times. The time taken for the ball to travel to the hitter is apparently sufficient for them to recover from their more-vulnerable post-pitch position.

Three of the college players were also subjected to tests in which they were instructed to avoid being hit by dodging out of the incident ball's path. 30 shots were recorded in the flight time range of 0.287-0.378 sec, and there were 18 observed failures out of 30 shots, for a failure rate of 60%. This is much worse than the 15% failure rate for the standing players (12 hits out of 79 shots) in this time range. Such dodging tests (100 shots) were also performed on four of the high school women softball players, and again the failure rate was found to be very high (75% in the 0.35-0.40 sec range, 65% in the 0.43-0.47 sec range, and 14% in the 0.50-0.54 sec range). It is therefore not recommended that players use such dodging motions to avoid being hit, but players never seem to attempt this anyway.

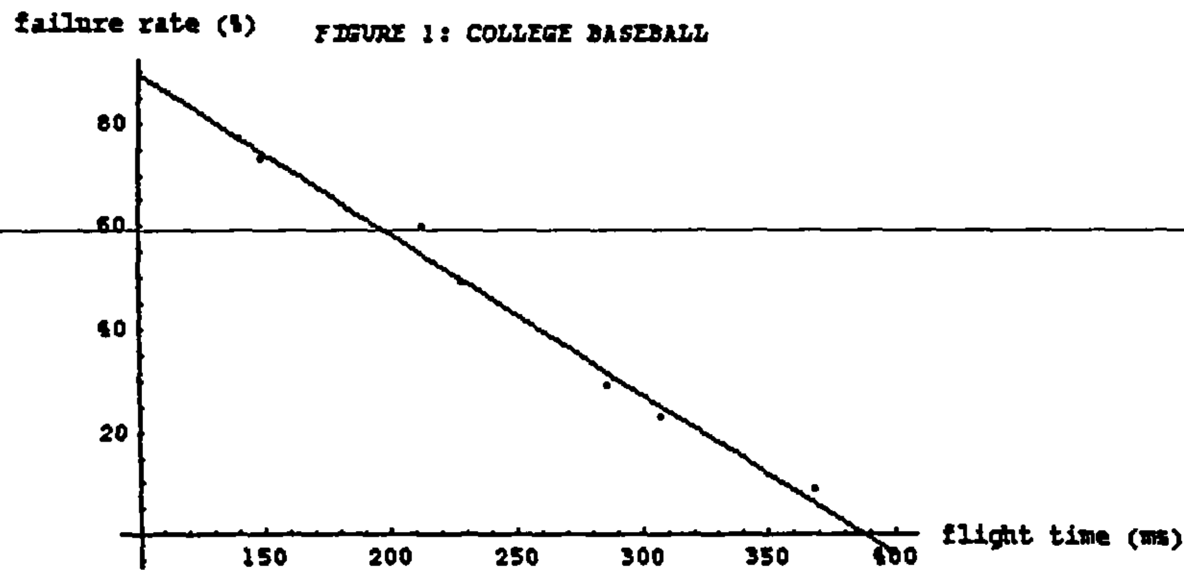
Additional standing tests at 20 ft were made on two of the college baseball players on another day, and the result was a slightly improved success rate. Since only 60 shots were recorded, however, this was not statistically significant. Tests on five of these players were also made at a 15-ft distance, and there were 51 failures out of 77 shots. This failure rate of 66% is less than anticipated from the trend observed in Table 2, but again this is not statistically significant.

4. ANALYSIS

Consider again the college baseball data in Table 2. The plot of the hit percent (sixth column) verses average flight time (third column) is given by the points in the graph shown in Figure 1. These points are seen to lie close to a straight line, and this is confirmed by the solid line shown in the graph, which is a least-squares quadratic fit to the data. This fit is indistinguishable from the straight line given by the equation

$$P = 120.6 - 312\,T,$$

where P is the hit percentage and T is the flight time in seconds. This linear expression provides an excellent fit to the data (χ^2 =2.56 for 6 degrees of freedom). This reveals a remarkable and unexpected regularity of the data, which does not seem to have been previously noted. It may have significant implications, which should be investigated in the future.



The women's high school softball results in Table 2 can be analyzed in exactly the same way. The hit-percent verses average-time data points are plotted in Figure 2. The best quadratic fit, shown in the Figure, is no longer a straight line, but the linear fit, shown in Figure 3, is as good. (χ^2 =4.21 with 5 degrees of freedom for the quadratic fit and χ^2 =7.32 with 6 degrees of freedom for the linear fit.)

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FIGURE 2: WOMEN HIGH-SCHOOL SOFTBALL

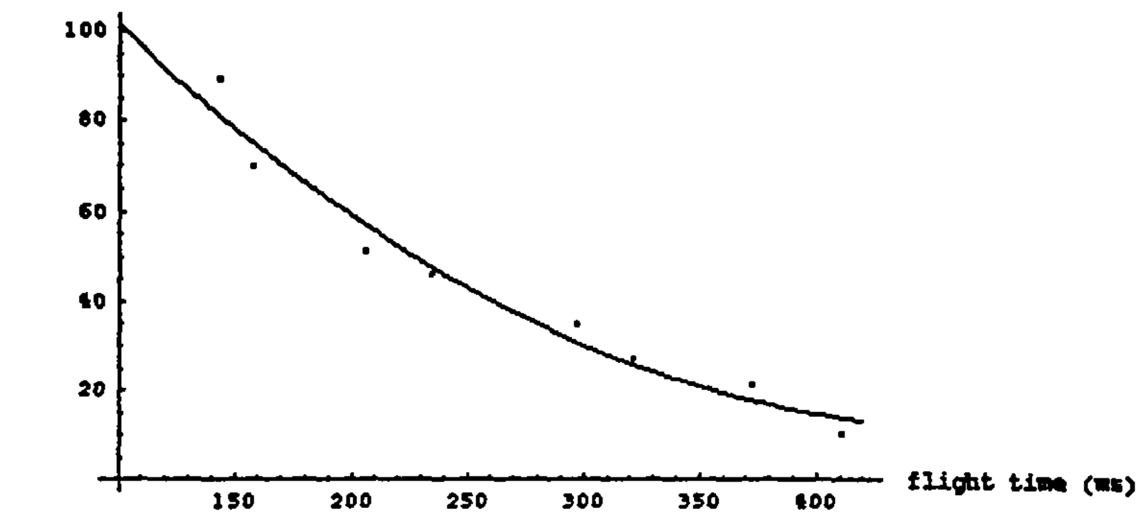
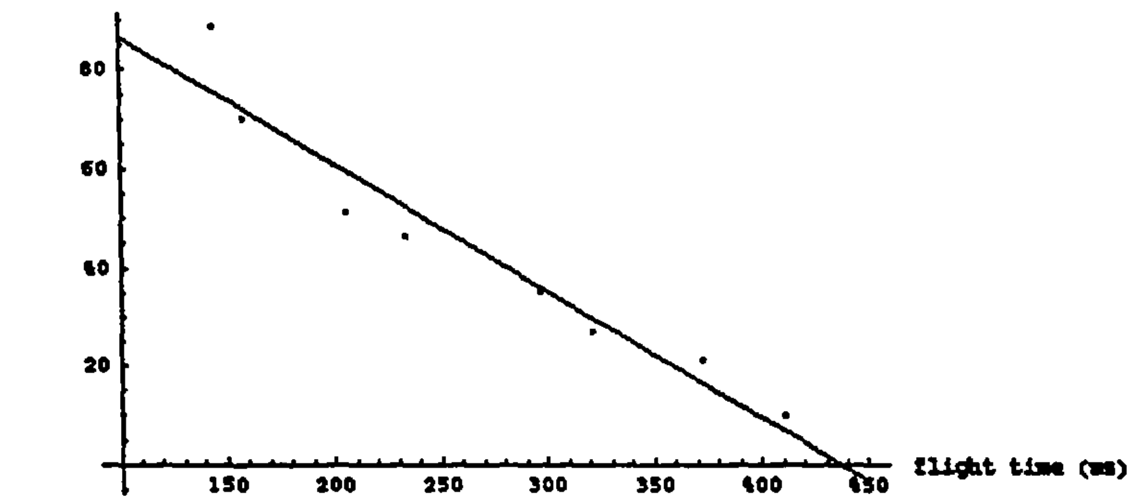
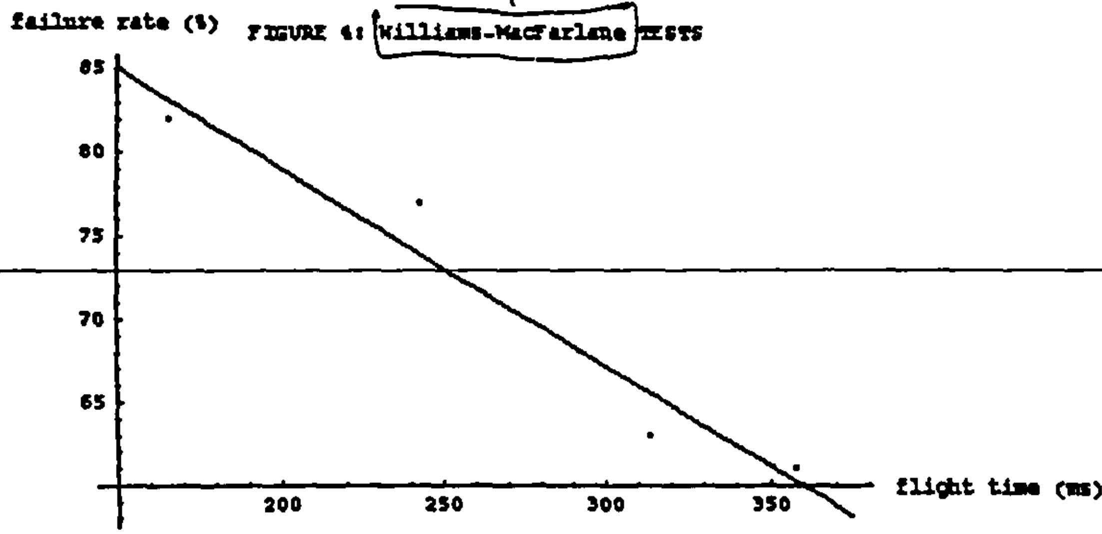


FIGURE 3: WOMEN HIGH-SCHOOL SOFTBALL



Given the above interesting straight-line fits to the failure-rate verses flight-time data, it is relevant to ask if there is independent evidence for this. It is, in fact, possible to extract supporting information from Reference 2 (Williams and MacFarlane). The reported tests had male college students attempt to catch tennis balls shot at speeds of 57 to 123 mph from 20 or 30 ft. (The stated flight times are from 0.111 to 0.353 sec, but these figures fail to take air-resistance into account, and this effect is even more important for tennis balls than for baseballs.) Reaction times are reported to increase from 0.16 to 0.18 sec as the ball speed increased, whereas the movement time remained approximately constant at about 0.10 sec. In Table III of this reference, the error percentages are given for each of the (not very accurately measured) four ball speeds. These results, converted to failure-rates verses flight-times, are plotted in Figure 4. The results are consistent with the measurements reported in this paper, and the indicated linear fit is seen to be good.

FIGURE 4: Williams-MacFarlane TESTS



For the remaining categories given in Table 3, the quantity of data is insufficient to warrant a display of graphs and χ^2 evaluations, but all of the results are seen to be consistent with linear fits as above. It will be interesting to see if more extensive future data confirms the accuracy of these fits.

5. HIT BALL SPEEDS

In the previous sections, the deflection success and failure rates were given as functions of the flight times of the incident ball. In order to convert these rates into functions of hit ball speeds, the distances between the hitters and the pitchers must be estimated. The distances between the home plate and the pitching mound are specified for each venue, but the actual flight distance is less than this for baseball, because of the forward motion of the pitcher during the pitch, and more than this for slow-pitch softball, because of the backward motion of the pitcher after the pitch. Typical values for these flight distances are 54 ft for conventional baseball, 42 ft for youth baseball, and 50 ft for slow pitch softball. Given such a distance and a flight time, the corresponding initial speed of the ball can be evaluated, again taking into account the important effects of air resistance. The results are given in Table 5.

TABLE 5: CATCH TEST SUMMARY				sec	feet	fps	mph
CATEGORY	SAMPLE	AGES	SHOTS	MAX HIT TIME	DISTANCE	MIN HIT SPEED	MIN HIT SPEED
College BB	8	18-22	320	0.368	54	155	105
High School BB	2	17	94	0.381	54	150	102
Recr. BB	4	20-54	154	0 387	54	147	100
Youth BB	1	11	40	0 417	42	107	73
Coll men SB	4	18-22	200	0.331	50	159	108
Coll. women SB	1	18	40	0 373	50	144	98
B-level men SB	2	19,24	100	0 395	50	133	91
H.S women SB	5	15-16	440	0 404	50	133	90
Girls (DWS) SB	2	13,14	80	0 413	50	127	87
Senior men SB	6	39-54	230	0 413	50	130	88

Table 4 is incorporated here as the first five columns. The sixth column gives the flight distance (in feet) between hitter and pitcher, as discussed above. The seventh column gives the initial hit ball speed (in feet per second) that results in the flight distance (column 6) being covered in the maximum hit time (column 5), and the final column gives this same speed in mph. The significance of these speeds is that there were no deflection failures for initial speeds ~~greater than the given minimum hit speed.~~

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What can we conclude from these results about the <u>safe</u> response times and hit ball speeds in baseball and softball? To completely answer this question, more data is needed, especially in the neighborhoods of the maximum failure times observed in these tests. It is also necessary to address the differences between these test conditions and game conditions in a quantitative way. It is finally necessary to decide on what is an acceptable level of injury for each category of play.

To illustrate how to proceed form the maximum failure times observed in these tests to recommendations for the values of safe response times and corresponding hit ball speeds for the various game categories, I consider first the college baseball data. Given that there were no failures out of 36 shots in the 0.376-0.398 sec time range (Table 2), that the maximum failure time was 0.368 sec (Table 4), and the regularity of the data as indicated in Figure 1, I conclude that a very conservative safe response time for college baseball players is 0.38 sec. To confirm this, it is necessary to obtain more data in the vicinity of 0.38 sec, so that the tail of the failure rate distribution can be fully explored. It can, however, be concluded now that the failure rate is less than 1 in 36 for flight times greater than 0.368 sec, with an 83% confidence level. It is very likely that the failure rate will be rather less than 1 in 36, but even this upper limit could be acceptable. If it is assumed that 1 in 100 hits are directed towards the pitcher and are such that an impact with the pitcher would result in a serious injury, and that 1 in 10 of these hits have flight times to the pitcher of less than 0.368 sec (hit speeds greater than 105 mph), then at most 1 in 36,000 hits would lead to a serious injury. If it is further assumed that there are 20 hits per game, than a pitcher would be possibly injured at most once in 1800 games.

Given that the safe response time is 0.38 sec, the safe maximum hit ball speed can be evaluated, again taking into account the important effect of air resistance. Assuming that the pitcher is 54 ft from the hitter at the time of the hit, it would require a hit speed greater than 104 mph for the ball to reach the pitcher in less than 0.38 sec. It is therefore concluded that, if the baseballs and bats are restricted to give rise to hit ball speeds of 104 mph or less, than the college baseball players will not be subjected to an inappropriate level of risk.

To determine the corresponding restriction on baseball bats, a pitch speed (at the bat) of 70 mph and a bat speed (at the point of impact) of 70 mph will be assumed. For a bat of typical weight and moment of inertia, this restricts the bat-ball COR to be 0.616 or less. If the ball COR is 0.54, this restricts the BPF to be at most 1.14. This was the maximum BPF of the bats used in the 1994 college baseball season. For this restriction to be meaningful, the ball properties (COR and compression) must also be restricted. See Appendix 2 for more details.

As a second example, I consider next the women's high school softball data in Tables 2 and 4. Given that the maximum failure time was 0.404 sec (Table 4) and that there were 0 hits out of 32 shots in the 0.405-0.433 sec time range, a very conservative safe response time for this category is 0.43 sec. A greater safety margin his been given here than for the men's college category because of the smaller slope of the linear fit of Figure 3 compared to Figure 1, because of the generally better response time of the male players, and because of the obvious desire to provide more leeway for these younger female players. Although the precise conclusion from the test results is that the probability of failure for response times of 0.405 sec or greater is less than 1 in 32 (82% confidence level), the above graph strongly suggests that the failure rate is considerably less than that. The 0.43-sec safe response time therefore is very reasonable. More data in the neighborhood of this time is, of course, needed to finalize this conclusion.

6. DISCUSSION

The results of the tests reported in this paper are summarized in Tables 2 – 5 and Figures 1 – 3. I have stressed that more tests are necessary to confirm these results, especially in the game categories in which less than 200 shots were recorded or less than 5 subjects were involved. What is needed in particular is additional measurements in the neighborhoods of the maximum failure times. When such additional information is incorporated into the determination of safe times and speeds, the recommended values may increase or decrease, but, given the conservative choices made here for these times and speeds, I expect that future contributions will decrease, rather than increase these estimates.

To illustrate this in detail, I consider again the measurements taken with the college baseball players. Since no deflection failures were observed for flight-times greater than 0.368 sec, I concluded that the failure rate is less than 1 out of 36 for times greater than 0.368 sec. When additional tests are made with flight-times greater than 0.368 sec, failures will inevitably occur. Let us say that when this new information is incorporated into the analysis, the resultant failure rate becomes 1 out of N, where N is an integer, presumably greater than 36. Let us also say that detailed observations reveal that 1 out of M game line-drives by batters result in a shot that would seriously injure the pitcher if it were not deflected. It would follow that 1 out of MN hits would actually seriously injure a pitcher. If this is the injury rate chosen to be acceptable, then the choice of 0.368 sec as the minimum safe response time will be confirmed. If this rate is greater then the chosen one, then the safe time must be increased, and if it is less than the chosen one, then this time must be decreased. The final choice for the safe time can thus be precisely determined.

The minimum safe flight time of 0.38 sec for college baseball corresponds to a maximum safe hit-ball speed of 104 mph. For typical college pitch and swing speeds (about 70 mph) and a typical bat weight and moment of inertia, this corresponds to a BPF of about 1.14. (See Appendix 2 for details.) Coincidentally, or perhaps not, this is the maximum measured BPF of the 1994 college bats (tested at 60 mph). In fact, in the 1995 SGMA-NCAA field test, where the pitch speeds were only 60 mph, the two bats with BPF's of 1.15 produced maximum observed hit speeds of 103 and 104 mph. The details of this test are given in Reference 3.

For the other categories given in Table 5, the maximum hit times are greater and the speeds are less. In using these results to estimate safe response times and hit ball speeds, due allowance must be made for the limited sample size or the perceived vulnerability of some categories. Thus, for male student baseball players, the times increase progressively as we proceed from college to high-school to youth venues, and the same is true for the female student softball venues. It is also interesting to note which categories have similar response times. The college (male) baseball players and (female) softball players are in the first class, with times of 0.37-0.38 sec. The high-school and recreational baseball players, B-level softball players, and high-school female softball players fall in the next class with times of 0.38-0.40 sec, and the final class consists of the youth baseball and softball players and the senior softball players with times of 0.41-0.42 sec.

It is also interesting to compare two individual subjects, the youngest, 11-year-old Dixie Youth pitcher Chance Murray, and the oldest, 54-year old retired player Jack MacKay. In the baseball tests, the young player had a maximum failure time of 0.417 sec and a no-failure range of 0.421-0.424 sec, whereas the old player had a maximum failure time of 0.363 sec and a no-failure range of 0.368-0.387 sec. Keep in mind that individual comparisons such as this are based on limited data and are therefore not necessarily statistically significant.

All of the data obtained in the tests have been seen to satisfy the linear relationships given by the straight-line fits shown in Figures 1 and 3. It was also shown that the data from Reference 2 could be similarly described. It will be interesting to see if future measurements confirm these remarkable regularities. If player response times were normally distributed, a faster than linear rise in failure percentage would be expected for decreasing times. It is possible that it is the decrease in reaction time with increasing ball speed that maintains the slower linear rise. These issues constitute an area for future research. It should be noted, in connection with data plots such as those in Figures 1 – 4, that error bars should be associated with the data points. Horizontal error bars, corresponding to the time ranges in Table 2, and vertical error bars, corresponding to the finite sample sizes, should be incorporated into the figures.

The importance of air resistance in the determination of flight times has been emphasized in this paper. To illustrate this, I note that the college baseball no-failure time range of 0.368-0.398 sec would have decreased to 0.355-0.379 sec if air resistance had been neglected. Although neglecting air drag decreases the calculated values of flight-times, it also decreases the calculated values of hit speeds corresponding to given flight time values, and these affects tend to cancel one another.

The differences between tests such as those reported in this paper and real game situations should be kept in mind. I have given some contributions to these differences is Section 1. Laboratory measurements are obviously useful, but they must supplemented by detailed information about actual injuries sustained in games. Such game injuries should be carefully monitored and recorded. It is in everyone's interest to keep baseball and softball among the safest sports.

ACKNOWLEDGEMENTS

I would like to thank the following people for their help with this research: Marty Archer and George Manning of H&B, for permission to use their facility in Texas; Jack, Kay, and Tripp MacKay for their hospitality in Texas, for supplying the subjects, and for help in running the tests; Jess Heald and Dan Pitsenberger of Worth, for funding the project; Andy Rodriguez of AMMCO, for introducing me to the bat performance issue; Dewey Chauvin of Easton, for sending me Reference 1; and Professor Allen Mincer of the NYU Physics Department, for useful conversations about statistics.

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APPENDIX 1: Air Drag Effects on Ball Trajectories

Consider a ball of mass m moving though the atmosphere with velocity $\vec{v}$ (speed $v = |\vec{v}|$) and with zero spin. In addition to the downward force mg of gravity, the ball experiences a resistive drag force

$$\vec{F}_D = -\tfrac{1}{2} C_D \rho A v^2 \hat{v},$$

where $\hat{v}$ is the unit vector in the direction of the velocity, A is the cross-sectional area of the ball, ρ is the density of air, and C_b is the drag coefficient. For smooth spheres and typical ball speeds, C_D is approximately equal to 0.5, but for baseballs and softballs, it is speed-dependent and its values are in the 0.3 to 0.4 range for speeds in the neighborhood of 90 mph.

If the ball has non-zero spin, then it experiences an additional force, which is perpendicular to the direction of the velocity. This force is directed upwards if the ball has bottom-spin, and downwards if it has topspin. The presence of bottom spin is useful for hits to the outfield because the upward (lift) force gives rise to longer hit distances. For line drives to the pitcher, however, this effect is negligible, and any spin imparted to the hit ball will be at the expense of hit ball speed. For a given pitch and swing speed, the fastest hit ball speed arises when no significant spin is imparted to the ball. In the determination of maximum hit speeds and minimum flight times to the pitcher, it will therefore be assumed that the hit ball has negligible spin.

The flight of the ball after it leaves the bat is determined by the differential equation

$$m\frac{d\vec{v}}{dt} = -mg\hat{y} - \tfrac{1}{2}C_D\rho A v^2\hat{v},$$

where m is the mass of the ball (the ball weights are about mg=6.5 oz for softballs and mg=5.2 oz for baseballs). Given the drag coefficient as a function of speed, and the initial velocity, this equation can be solved numerically to obtain the trajectory $\vec{r}(t)$. The ball's position $\vec{r}(t)$ and velocity $\vec{v}(t) = \frac{d\vec{r}(t)}{dt}$, at any time t after the hit, is thus obtained. The time of flight to any specified distance can then be evaluated.

In the evaluation of the flight times between the cannon and the subjects used in this paper, it was assumed that the hit balls were directed, at the measured initial speed, towards the face of the subject standing at the measured distance from the cannon. In the evaluation of the flight times between a hitter and a pitcher, it was assumed that the hit balls were directed, at the specified initial speed, at the face of the pitcher standing 54 feet from the hitter.

APPENDEX 2: Bat Performance

In the text of this paper, data on response times and corresponding hit ball speeds were presented and analyzed. To relate this data to bat performance, I will use the following equation for hit ball speed v':

$$v' = \frac{V(1+e) + v(e-k)}{1+k},$$

where V is the bat swing speed at the impact point, v is the pitch speed, e is the COR between the bat and ball, and k is the combination

$$k = \frac{w}{W} + \frac{w(R-a)^2}{I - Wa^2},$$

in terms of the ball weight w, bat weight W, bat center of mass a, bat moment of inertia I, and impact distance R. (a, I, and R are relative to a fixed point six inches from the bat knob.) The hit speed is seen to depend and many factors: bat properties (W, a, I), ball properties (w), ball-bat properties (e), pitcher properties (v), and hitter properties (V, R).

To simplify these expressions, I use the factorization $e=Be_0$, where e_0 is the ball COR and B is the bat performance factor (BPF). B, defined as the COR between the bat and a test ball divided by the COR of the test ball, is approximately a property of the bat alone. I also will assume that the impact point R is the center of percussion of the bat. This point is approximately the point of maximum hit speed. Then the hit speed depends separately on the bat properties (B, W, I), ball properties (e_0, w), and player speeds (v, V).

For further simplification, I will use the fact that v' depends only weakly on the bat weight W and MOI I. This fact is a consequence of the decrease in bat speed V with increasing W or I. This leads to optimal values of these bat properties, which are about W = 30 oz and I = 9675 oz-in^2 for a typical adult male hitter. I will also use 70 mph as the typical bat swing speed V at the COP for such a hitter, and assume that the pitch speed v (at the bat) is 70 mph for college baseball and 30 mph for slow-pitch softball. Finally, the ball parameters will be those specified by most ballgame associations: w = 5.25 oz and e_0 = 0.54 for baseball and w = 6.5 and e_0 = 0.47 for softball. With these assumptions, k = 0.25 for baseball and k = 0.30 for softball.

The above equation for hit speed v' can now be used to translate the maximum safe values of v' into maximum safe values of BPF B. For college baseball, v' = 104 mph was the maximum safe hit ball speed, and this gives e = 0.554 as the maximum safe bat-ball COR at the ball-bat relative speed V + v = 140 mph. The BPF tests and ball COR measurements are currently performed at the relative speed of 60 mph, and so to compare this result to the existing bat BPF measurements, the value of the baseball COR e_0 = 0.54 at 60 mph must be extrapolated from 60 to 140 mph. Using the existing information on how baseball CORs decrease with increasing speed, the result is that e_0 = 0.485 at 140 mph. Therefore, the maximum hit speed of 104 mph corresponds to a maximum BPF of 0.554/0.485 = 1.14. This is the maximum BPF of the bats used in the 1994 college baseball season. For men's B-level softball, the maximum safe hit speed of 94 mph corresponds to a maximum ball-bat COR of 0.612 at 100 mph, and a maximum BPF of 1.38. Since this is much greater than the BPF of 1.20 allowed by the USSSA, player safety does not appear to be a factor in the determination of bat performance limits in softball,

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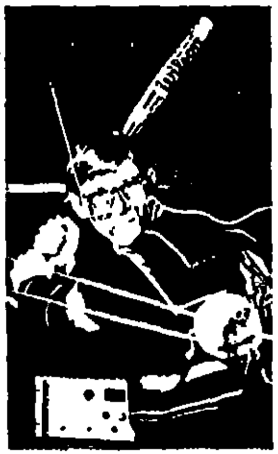

A. Terry Bahill

KEEP YOUR EYE ON THE BALL

The Science and Folklor ... *ball*

Robert G. Watts and A. Terry Ba..il

"Well researched and entertaining...will be of interest to both casual and dedicated fans of the great American game."
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Watts and Bahill—engineers by vocation, baseball *fans* by avocation—have devised a series of experiments that put some of baseball's most cherished myths to the test. The result is a highly informative and entertaining guide that combines absorbing anecdotes and historical developments with research findings to provide the scientific slant on some classic baseball conundrums. You'll find the details on: the mechanics and physics of pitching and hitting • why the curveball curves • the flyball and the effect of backspin and topspin on its flight • the scientific evidence about eye-hand coordination in batters • and a fascinating new slant on baseball statistics.

Robert G. Watts teaches in the Department of Mechanical Engineering at Tulane University. Having more than a mere theoretical interest in the game, he pitched as a young man for the semiprofessional Bayou Latanache Baseball Club—where he gained first-hand knowledge of spitballs, flyballs, and a healthy familiarity with insider-baseball lore.

A. Terry Bahill is Professor in the Department of Systems and Industrial Engineering at the University of Arizona. He has been investigating the brain's motor functions since 1971. Actively pursuing experiments in the science of baseball for many years, he has developed a measuring device that strengthens a player's ability to follow the pitch. He recently worked with members of the San Francisco Giants in tests to determine an individual's ideal bat weight.

ISBN 0-7167-2248-8

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KEEP YOUR EYE

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ON THE BALL

KEEP YOUR EYE ON THE BALL

The Science and Folklore of Baseball

Robert G. Watts
A. Terry Bahill

W. H. FREEMAN AND COMPANY
NEW YORK

Library of Congress Cataloging-in-Publication Data

Watts, Robert G.
Keep your eye on the ball : the science and folklore of baseball / by Robert G. Watts and A. Terry Bahill.
p. cm.
Includes bibliographical references (p.).
ISBN 0-7167-2104-X
1. Physics. 2. Baseball. 3. Force and energy. I. Bahill, A. Terry II. Title.
QC26.B38 1990
796.35701'53—dc20 89-49293
CIP

1 2 3 4 5 6 7 8 9 0 VB 9 9 8 7 6 5 4 3 2 1 0

The cartoons on pages 25, 41, 57, 85, 135, 164, 180, and 195 are © 1990 by Sidney Harris.

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ficient of restitution had not been practiced before the mid-1950's. In an article in *Collier's* magazine, Tom Meany[3] reported that Spalding Bros., Inc. claimed that there had been no changes in the specifications in manufacturing their baseballs for at least three decades. Conversely, there is a National Bureau of Standards report stating that official major league balls in 1943 were found to have coefficients of restitution of 0.41. It has been speculated that during World War II, the quality of the material used in the manufacture of baseballs was inferior to that used in other years. This coefficient of restitution of 0.41 is much lower than the value of 0.55 that is required of the present-day ball. The fact that the home run explosion was already well on its way by the 1940's casts some doubt on the "livelier ball" theory.

The year 1987 was a banner year for home run hitting, and specula-tions about the increased coefficient of restitution continued to abound. Baseball manufacturers continued to deny allegations of "rab-bit" balls. *USA Today* reported on July 3, 1987, that tests of 1987 and 1977 baseballs performed by Haller Testing Laboratories showed only the slightest changes. The coefficient of restitution has, according to their results, *declined* by 0.4 percent during that 10-year period.

A more reasonable explanation of what is behind the trend toward more and more home runs is the "livelier ball player" theory. It was Babe Ruth who really started the trend toward more home runs in 1919. When it was pointed out to Ruth in 1930 that he made more money than President Hoover, Ruth reportedly responded, "I had a better year." Home run hitters generally began having much better years (financially) than those who merely hit singles for higher averages. As Meany said, "The money's in the big end of the bat." Hitters are concentrating more on hitting home runs. As is the case in other sports, diet and other factors have also led to healthier, stronger players.

◆ *The Best Bat Weight: From the Principles of Physics* ◆

The bat might have played at least as important a role as the ball in the home run explosion. According to statistics compiled by Hillerich and Bradsby, manufacturers of the Louisville Slugger bat, the average weight of bats used by top players decreased from about 40 ounces in the

1920's to about 32 ounces in the 1950's.[3] This was a period during which home run production increased dramatically. However, not all batters follow the same trend. According to Dan Gutman in a 1988 *Discover* article,[4] to make the bat heavier "Ted Kluszewski of the Cincinnati Reds used to sink tenpenny nails into his bat barrel. St. Louis Browns first baseman[6] George Sisler banged in Victrola needles." To make the bat lighter, many players, including Houston's Billy Hatcher and Detroit's Norm Cash, have drilled a big hole in the end of the bat and filled it with cork. In an attempt to change the coefficient of restitution some players have stuffed the bat with Super Balls. Gutman[4] says, "Back in 1974 Graig Nettles of the Yankees took a vicious swing in the fifth inning of a game against Detroit, splitting his bat as it made contact. Out bounced six Super Balls." Brancazio[2] cites an article in *Newsday* magazine saying that "a hitter sometimes hollows a bat and stuffs it with a spongy substance like cork or rubber balls to make the bat expand explosively . . . upon impact with a ball." This is nonsense, as pointed out by Brancazio. In fact, as long as the structural integrity of the bat is not destroyed by drilling too large a hole, the coefficient of restitution of the bat-ball collision is unchanged. Note that the outer surface of the bat shown in Figure 35 is undeformed during the collision with the ball. A change in the coefficient of restitution of the ball-bat combination is almost certainly not responsible for the most recent increase in home run hitting. In the remainder of this chapter and in Chapter 6 we will explore some other possibilities. Let us now see what the theory of collisions can say about this important question.

Now that we have some understanding of the coefficient of restitu-tion, or the "bounciness" that occurs when bat meets ball, we have a way of relating the speeds of two objects before and after the collision to the physical properties of the colliding objects. This allows us to use the equation for conservation of momentum

$$m_1 v_{1b} + m_2 v_{2b} = m_1 v_{1a} + m_2 v_{2a}$$

with the equation for the coefficient of restitution

$$e = -\frac{v_{1a} - v_{2a}}{v_{1b} - v_{2b}}$$

to obtain expressions for both the bat and ball speed immediately after the collision. We find that

$$v_{1a} = \frac{(m_1 - em_2)\, v_{1b} + (m_2 + em_2)\, v_{2b}}{m_1 + m_2}$$

and

$$v_{2a} = \frac{(m_1 - em_1)\, v_{1b} + (m_2 + em_1)\, v_{2b}}{m_1 + m_2}$$

Much can be learned from these two equations, so let's dwell on them for awhile.

First, since v_{1b} is a negative number and v_{2b} is a positive number (the objects are moving in opposite directions), v_{1a}, the speed of the ball after the collision, always increases with e. Also, as long as $m_1 - em_2$ is negative (the weight of the bat is larger than $1/e$ times the weight of the ball), v_{1a} increases when $-v_{1b}$ increases. This means that fastballs can be hit harder than slow pitches, all other things being equal.

Finally, the equation for v_{1a} tells us that, all other things being constant, the speed of the ball as it leaves the bat increases as the weight of the bat increases. Suppose, for example, that the bat is much lighter than the ball. Omitting the term m_2 from the immediately preceding equations, that is, assuming m_2 is close to zero, shows that in that case

$$v_{1a} = v_{1b}$$

which means the ball zooms past with undiminished speed. We also find that

$$v_{2a} = (1 - e)\, v_{1b} + ev_{2b}$$

(the bat flies backwards). Suppose, on the other hand, that the bat weighs very much more than the ball. In such a case, terms involving m_1 in the equations for v_{1a} and v_{2a} can be dropped. The results are then

$$v_{1a} = -ev_{1b} + (1 + e)v_{2b}$$

and

$$v_{2a} = v_{2b}$$

The collision with the ball does not affect the speed of the huge bat. *For a given bat speed*, this is the largest velocity that can be imparted to the ball. According to this reasoning, bats should be as heavy as the rules will allow.

There is, of course, a problem with this kind of analysis. A little thought tells us that if the bat is too heavy, the batter cannot control it well enough to make good contact with the ball. Even if he could make contact with the ball, the bat speed before contact would be smaller than that which could be attained with a lighter bat. What the analysis above does not account for is that the larger m_2, the smaller the bat speed before the collision, v_{2b}. What we have here is a case of conflicting effects.

This is as good a time as any to introduce a much-overlooked fact about the practical use of scientific theories. Scientific ideas can be used to explain what is happening in the world around us, and, in many cases, to predict better ways of doing things. But we must be quite specific in the way we ask questions. Almost all really interesting scientific problems involve conflicting factors. In the case of hitting a baseball with a bat, we found that, strictly from the point of view of momentum considerations, the speed of a baseball leaving the bat with a given bat speed is maximized by making the bat mass (or weight) as large as possible. A very large bat would, however, be hopelessly unwieldy. From the standpoint of bat control and accuracy the bat should be extraordinarily light. The equation

$$v_{1a} = v_{1b}$$

and the equation

$$v_{2a} = (1 - e)v_{1b} + ev_{2b}$$

as well as our intuition tell us that such a bat would simply be knocked from a batter's hands. Surely there is an optimum bat weight between these two extremes. But optimum in what sense?

Momentum effects associated with the collision itself tell us that for a given speed, we need a massive bat. We also know, however, that the smaller the bat, the higher the bat speed that can be obtained. The speed with which a particular batter can swing his weapon depends on how much efiergy he can put into his swing. To resolve our conflict, and to learn more about the optimum bat and the optimum swing, we need to stop looking at only the bat and the ball. We must now consider the human being swinging the bat.

◆ *The Best Bat Weight: From the Principles of Physics and Physiology** ◆

The speed of a baseball after its collision with a bat depends on many factors, not the least of which is the weight of the bat. One professional baseball team (St. Louis Cardinals) says the weight of the bat is determined by "the player's personal preference"; another (New York Yankees) says, "Each individual player determines the style of bat he prefers." These players have very little real scientific data to help them support their preferences. In this section we present data to help an individual player to decide if his or her preference is the most effective bat weight. Knowing the ideal bat weight can eliminate time-consuming and possibly misleading experimentation by ball players.

To find the best bat weight we must first re-examine the conservation of momentum equations for bat-ball collisions. For the science of baseball the distinction between mass and weight is not critical, and so we will substitute weight for mass in the equation for the conservation of momentum to produce

$$w_1 v_{1b} + w_2 v_{2b} = w_1 v_{1a} + w_2 v_{2a}$$

Keep in mind that we are assuming the weight of the batters arms has *no* effect on the collision (this may be an important assumption). We want to solve for the ball's speed after its collision with the bat—called the *batted-ball speed*—but first we should eliminate the bat's speed after the collision, because it is not easily measured. We can use the equation for the coefficient of restitution to solve for v_{2a}, substitute the result into the equation for the conservation of momentum, and solve for the ball's speed after its collision with the bat. The result is

*This section was based on Bahill and Karnavas.[3]

$$v_{1a} = \frac{(w_1 - ew_2)v_{1b} + (w_2 + ew_2)v_{2b}}{w_1 + w_2}$$

This means that the ball's speed after the collision will depend on the weight of the ball and bat, the coefficient of restitution, and the precollision speeds of the ball and bat.

Kirkpatrick[1] assumed that the optimal bat weight would be the one that "requires the least energy input to impart a given velocity to the ball." This definition in conjunction with the immediately preceding equation yields

$$\left[\frac{w_2}{w_1}\right]_{\text{optimal}} = \frac{v_{1a} - v_{1b}}{v_{1a} + ev_{1b}}$$

If we now make the reasonable assumptions that

$w_1 = 5.125$ oz, the weight of the ball

$e = 0.55$, the coefficient of restitution of a baseball

$v_{1b} = -80$ mph, a typical pitch speed

$v_{1a} = 110$ mph, the ball speed needed for a home run

we can solve the immediately preceding equation to find that the *optimal bat weight* is 15 ounces!

Brancazio[2] has written an excellent theoretical analysis of bat-ball collisions. He considered not only the bat's translation but also its angular rotation about two axes. He found that the ball's speed after the collision with the bat depends on

1. the energy imparted by the body and arms;
2. the energy imparted by the wrists;
3. the speed of the pitch;
4. the point of collision of the ball with respect to
   a. the center of percussion,
   b. the center of mass,

c. the end of the bat,

d. the maximum energy transfer point, and

5. the weight of the bat

However, by assuming that a professional baseball player exhibited normal values for each of these dependencies, he also concluded that the *optimal bat weight* is about 15 ounces.

These conclusions cannot help professional baseball players, who must use solid wood bats, because a 15-ounce solid wood bat would only be about 15 *inches* long! Such a bat would be far smaller than any bat that is now used in professional baseball. A typical major league bat weighs about 32 ounces. Babe Ruth normally used a 44-ounce bat, and sometimes used bats weighing more than 50 ounces. On the other hand, a fungo bat, a bat used for hitting fly balls in practice sessions, weighs about 23 to 24 ounces. One might take this to mean it is closer to the optimum weight. However, a fungo bat is used to hit balls that have initial speeds v_{1b} of practically zero, so a re-examination of the conservation of momentum equation indicates that for that case, the bat should weigh the same as the ball, about $5^1/_4$ ounces.

These conclusions may help explain why people choke up on the bat; choking up makes the bat effectively shorter, moves the center of mass closer to the hands, thereby reducing the moment of inertia, and in essence makes the bat act like a lighter bat. Several reasons have been advanced for buying a long bat and choking up on it. First, a longer bat must be made from wood that has straighter grain. Therefore bat manufacturers use the best wood for the longer bats, and bats made from the best wood do not break as easily. Secondly, using a longer bat allows the batter to change the effective weight of the bat during his time at bat. Al Rosen recalled that Ted Williams and Mickey Mantle did not choke up with no strikes. If the pitcher got one strike on them, they choked up a half inch. If the pitcher got two strikes, they choked up an inch. This conclusion could also help explain the great popularity of aluminum bats. The manufacturers can make them lighter while maintaining the same length and width.

It might also explain why so many professional players are "corking" their bats.[4,6] "Players," says Stephen Hall in an issue of *Science83* magazine, "have been known to drill a half-inch diameter hole in the fat end of the bat—anywhere from eight to fourteen inches deep—and . . . fill it with cork." Norm Cash freely admits to having used a corked bat in 1961, when he won the American League batting title by

batting .361. Presumably, he also used a corked bat in 1962 when he only hit .243. The advantage of corking the bat is that it makes the bat lighter. For some batters this is advantageous.

Both Kirkpatrick's and Brancazio's physics studies were limited by their explicit assumptions. Kirkpatrick assumed that the optimal bat was the one that required the smallest bat kinetic energy. Brancazio's calculations of the optimal bat weight were based on the assumption that the "batter generates a fixed quantity of energy in a swing," independent of the bat weight. We will now extend these studies by allowing the amount of energy imparted to the bat by the batter to depend on bat weight.

Physiologists have long known that muscle speed decreases with increasing load.[7-10] This is why bicycles have gears. The rider can keep muscle speed in its optimal range while bicycle speed varies greatly. Therefore, to discover how muscle properties of individual ball players affect their best bat weights, we measured the bat speeds of many batters swinging bats of various weights. We plotted the data of bat speed versus bat weight, and used this to help calculate the best bat weight for each batter.

◆ *The Bat Chooser™ Instrument* ◆

Our instrument for measuring bat speed, the Bat Chooser,* has two vertical light beams, each with associated light detectors (similar to the electric eyes on elevator doors). The subjects were positioned so that when they swung the bats the center of mass of each bat passed through the light beams. A computer recorded the time between interruptions of the light beams. Knowing the distance between the light beams and the time required for the bat to travel that distance, the computer calculated the speed of the bat's center of mass for each swing. Our computer sampled every 16 microseconds. In all cases our velocities are accurate to better than 1%.

Each player was positioned so that bat speed was measured at the point where the subject's front foot hit the ground. This is the place where most players reach maximum bat speed and therefore where they hit the ball with maximum force.

*Bat Chooser is a trademark of Bahill Intelligent Computer Systems. A patent is pending.

We told the batters to swing each bat as fast as possible while still maintaining control. We told the professionals to "pretend you are trying to hit a Nolan Ryan fastball."

In our experiments each adult subject swung six bats through the light beams. The bats varied from superlight to superheavy, yet they had similar lengths and weight distributions. In our developmental experiments we tried about three dozen bats. We used aluminum bats, wood bats, plastic bats, infield fungo bats, outfield fungo bats, bats with holes in them, bats with lead in them, major league bats, college bats, softball bats, Little League bats, brand new bats, and bats over 40 years old. In one set of experiments we used the six bats shown in Figure 37 and described in Table 2. These bats were about 35 inches long, with the center of mass about 23 inches from the end of the handle of each bat.

For Little League players we changed to a different set of bats. They had to be lighter and fewer in number. For our final experiments we used the set described in Table 3. However, even with this set we saw signs of fatigue in half our subjects.

In a 20 minute interval of time, each subject swung each bat through the instrument five times. The order of presentation was randomized.

TABLE 2 Characteristics of the Six Adult's Bats

Name	*Weight (oz)*	*Length (in)*	*Distance From the End of the Handle to Center of Mass (in)*	*Composition*
F	49.0	35.0	22.5	Aluminum bat filled with water
E	42.8	34.5	24.7	Wood bat, drilled and filled with lead
D	33.0	35.5	23.6	Regular wood bat
C	30.6	34.5	23.3	Regular wood bat
B	25.1	36.0	23.6	Wood fungo bat
A	17.9	35.7	21.7	A wooden bat handle mounted on a threaded steel lamp pipe with a 6-oz weight attached to the end

[From A. T. Bahill and W. J. Karnavas, *Biological Cybernetics*, 62:89–97, 1989.]

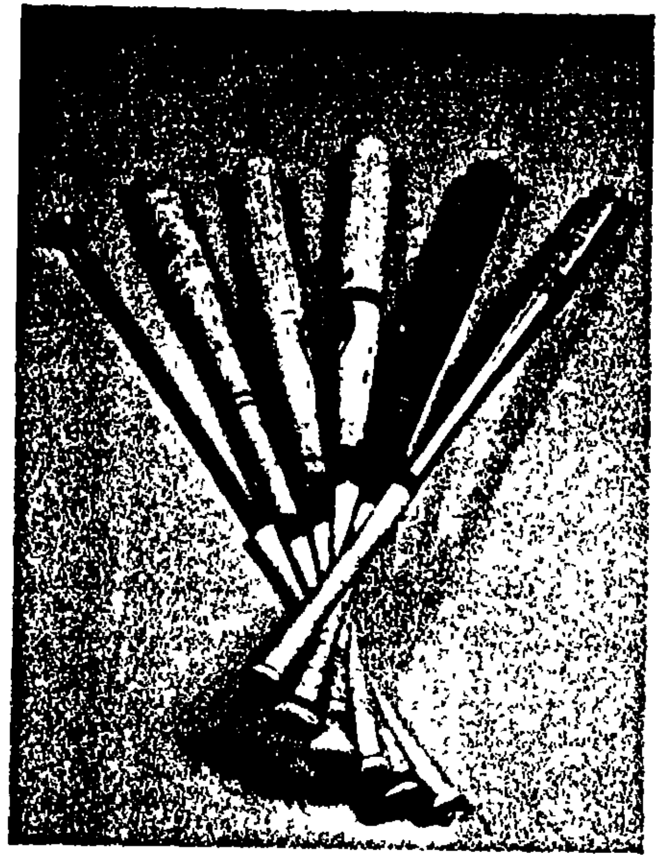

FIGURE 37. *The bats used in our final experiments; the lightest is on the left, the heaviest on the right. These bats are described in Table 2. (Photo: Richard Harding).*

TABLE 3 Characteristics of the Four Boy's Bats

Name	*Weight (oz)*	*Length (in)*	*Distance to Center of Mass (in)*	*Composition*
A	40.2	29.9	17.8	Wood bat with iron collar
B	5.2	31.3	17.6	Plastic bat
C	25.1	28.0	17.3	Wood bat
D	21.1	28.8	17.0	Aluminum bat

[From A. T. Bahill and W. J. Karnavas, *Biological Cybernetics*, 62:89–97, 1989.]

The selected bat was announced by a DECtalk® speech synthesizer, for example, "Please swing bat Hank Aaron, that is, bat A." We recorded the bat weight and the linear velocity of the center of mass for each swing.

◆ *The Force-Velocity Relationship of Physiology* ◆

When bat speeds measured with this instrument were plotted as a function of bat weight, we obtained the typical muscle force–velocity relationship shown in Figure 38. The ball-speed curve and the term *Ideal bat weight* shown in this figure will be discussed in a later section. This

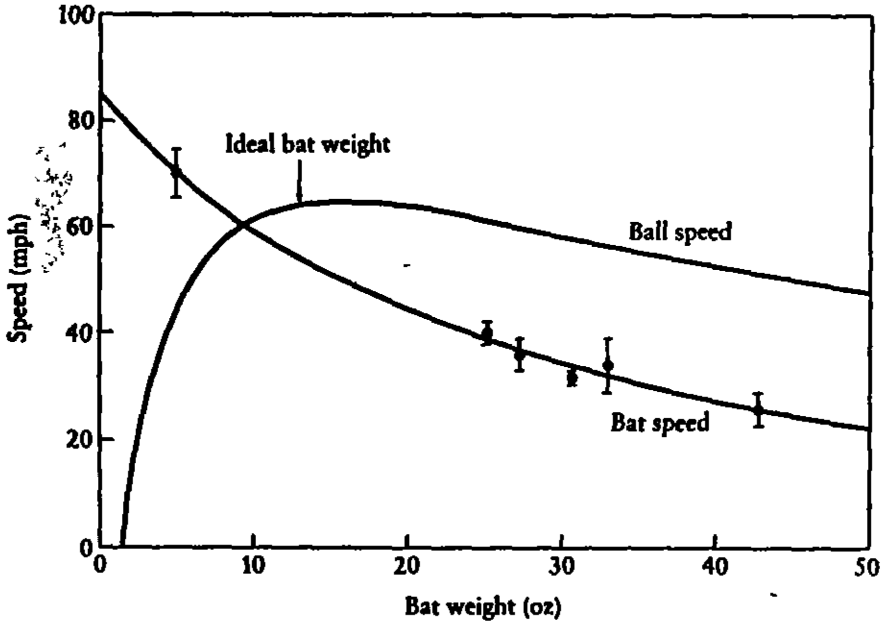

FIGURE 38. *Bat speed and calculated ball speed after the collision both as functions of bat weight for a 40-mph pitch to Alex, a ten-year-old Little League player. The dots represent the average of the five swings of each bat; the vertical bars on each dot represent the standard deviations. These data were collected with a different set of bats than that described in Table 3. [From A. T. Bahill and W. J. Karnavas,* Biological Cybernetics, *62:89–92, 1989.]*

force-velocity relationship shows that the kinetic energy ($^1/_2\, mv^2$) put into a swing was zero when the bat weight was zero, and also when the bat was so heavy that the speed was reduced to zero. The bat weight that allowed the batter to put the most energy into the swing, the *maximum-kinetic-energy bat weight*, occurred somewhere in between. This led to the suggestion that the batter might choose a bat that would allow maximum kinetic energy to be put into the swing. Figure 39 shows the kinetic energy as a function of bat weight for a member of the San Francisco Giants. This batter could impart the maximum energy to a bat weighing 46.5 oz.

This maximum-kinetic-energy bat weight does not, however, tell us the bat weight that will make the ball leave the bat with the highest speed. To calculate this weight we must couple the muscle force–velocity relationship to the equations for conservation of momentum. We can then solve the resulting equations to find the bat weight that

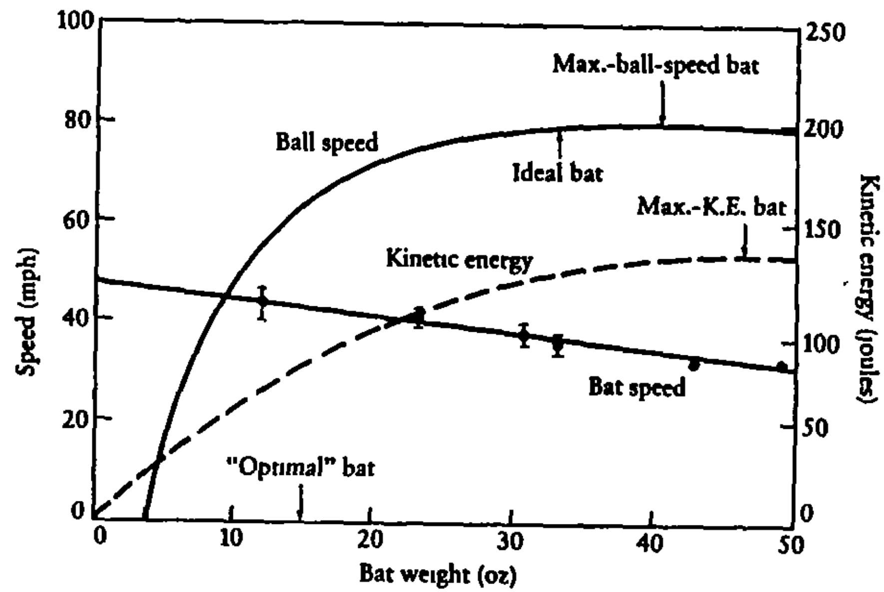

FIGURE 39. *Bat speed, kinetic energy given to the bat, and calculated ball speed after the collision, all as functions of bat weight for an 90-mph pitch for a member of the San Francisco Giants baseball team. Data for other professional baseball players were similar. These data were collected with a different set of bats from that described in Table 2. [From A. T. Bahill and W. J. Karnavas,* Biological Cybernetics, *62:89–97, 1989.]*

would allow a batter to produce the greatest batted-ball speed. This would, of course, make a potential home run go the farthest, and give a ground ball the maximum likelihood of getting through the infield. We call this weight the ***maximum-batted-ball-speed bat weight.***

◆ *Coupling Physics to Physiology* ◆

Next we coupled the equations of physics to the equations of physiology. Over the last half century physiologists have used three equations to describe the force-velocity relationship of muscles: that for the straight line ($y = Ax + B$), that for the hyperbola ($[x + A][y + B] = C$), and that for the exponential ($y = Ae^{-Bx} + C$).[11] Each of these equations has been best for some experimenters, under some conditions, with certain muscles, but usually the one for the hyperbola fits the data best. In our experiments we fit all three and chose the equation that gave the best fit to the data of each subject's 30 swings. For the data of Figure 39, the best fit was: bat speed (in mph) = −0.34 bat weight (in oz) + 48, or

$$v_{2b} = -0.34w_2 + 48$$

Next we substituted this relationship into the equation

$$v_{1a} = \frac{(w_1 - ew_2)v_{1b} + (w_2 + ew_2)v_{2b}}{w_1 + w_2}$$

yielding

$$v_{1a} = \frac{(w_1 - ew_2)v_{1b} + (w_2 + ew_2)(Aw_2 + B)}{w_1 + w_2}$$

We then took the derivative with respect to the bat weight, set this equal to zero, and solved for the maximum-batted-ball-speed bat weight. The result is

$$w_{2mbbs} = \frac{-w_1A - \sqrt{w_1^2A^2 - Aw_1(B - v_{1b})}}{A}$$

For the data of Figure 39 this was 40.5 oz.

The physics of bat-ball collision predicts an optimal bat weight of 15 oz. For the professional baseball player of Figure 39, the physiology of the muscle force–velocity relationship reveals a maximum-kinetic-energy bat weight of 46.5 oz. When we coupled the equation $v_{2b} = -0.34w_2 + 48$, fit to the force-velocity data of Figure 39 to the equation derived from the coefficient of restitution and the principle of conservation of momentum for bat-ball collisions, we were able to plot the ball speed after the collision as a function of bat weight, also shown in Figure 39. This curve shows that the maximum-batted-ball-speed bat weight for this subject was 40.5 oz, which is heavier than that used by most batters. However, this ball speed curve is almost flat between 34 and 49 oz. There is only a 1.3 percent difference in the batted-ball speed between a 40.5-oz bat, and the 32-oz bat normally used by this player. Evidently the greater control permitted by the 32-oz bat outweighs the 1.3 percent increase in speed that could be achieved with the 40.5 oz bat.

◆ *Ideal Bat Weight™* ◆

The maximum-batted-ball-speed bat weight is probably not the best bat weight for any player. A lighter bat will give a player better control and more accuracy. Obviously a trade-off must be made between maximum batted-ball speed and controllability. Because the batted-ball speed curve of Figure 39 is so flat around the point of the maximum-batted-ball-speed bat weight, we believe there is little advantage in using a bat as heavy as the maximum-batted-ball-speed bat weight. Therefore, we have defined the *Ideal Bat Weight** to be the weight at which the ball speed curve drops 1 percent below the speed of the maximum-batted-ball-speed bat weight. Using this criterion, the ideal bat weight for this subject is 33 oz. We believe this gives a reasonable trade-off between distance and accuracy. Of course, this is subjective and each player might want to weigh the two factors differently. It does, however, give a quantitative basis for comparison. The player of Figure 39 was typical of the San Francisco Giants players whom we studied, as shown in Table 4,

*Ideal Bat Weight is a trademark of Bahill Intelligent Computer Systems.

TABLE 4 Summary of Data for the 28 San Francisco Giants

Maximum Batted-ball Speed (mph)		Ideal Bat Weight (oz)		Actual Bat Weight (oz)		Maximum Kinetic Energy (joules)	
Average	Range	Average	Range	Average	Range	Average	Range
99	80–122	31.7	26.25–37.00	32.3	31–34	270	133–408

except that his swings were slower but more consistent than most. He is a control hitter.

For contrast, in Figure 40 we show the data of a San Francisco slugger who was less consistent. However, his slugging average was over .600. His data are best fit with bat speed (in mph) = −0.39 bat weight (in ounces) + 63. Substituting this into the equation for v_{1a} and performing our other calculations yield an ideal bat weight of 32 ounces. It is surprising that although the two players and their data as shown in Figures 39 and 40 are so dissimilar, their ideal bat weights are nearly the

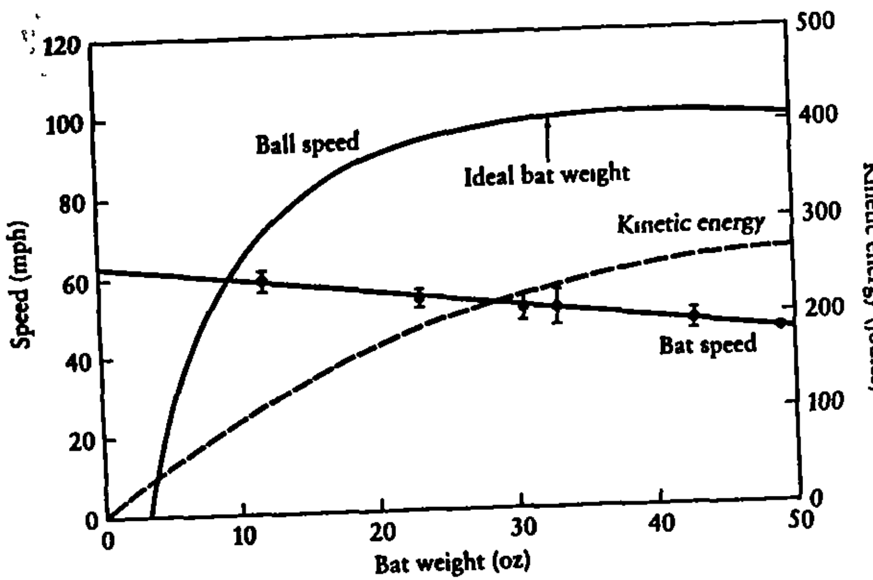

FIGURE 40. *Bat speed, kinetic energy, and calculated ball speed after the collision, for a different member of the San Francisco Giants baseball team.*

TABLE 5 Measured Ideal Bat Weight

Team	Mean Ideal Bat Weight (oz)	Standard Deviation	Pitch Speed	Number of Subjects
San Francisco Giants	31.7	3.8	90	28
University Baseball	28.3	2.8	80	11
University Softball	27.8	3.7	60	12
Little League	20.1	3.4	40	11
Slow Pitch Softball	19.4	1.0	20	4

[From A. T. Bahill and W. J. Karnavas, *Biological Cybernetics*, 62:89–97, 1989.]

same. These data contrast dramatically with data from the 10-year-old boy of Figure 38. His data are best fit with this hyperbola:

$$(w_{bat} + 28.0) \times (\text{bat speed} + 12.8) = 2728$$

Substituting this into the equation for v_{1a} and performing our other calculations yields an ideal bat weight of 15 ounces.

The ideal bat weight varies from person to person. Table 5 shows the means and standard deviations of ideal bat weights for batters in various organized leagues. These calculations were made with the pitch speed each player was most likely to encounter, for example, 40 mph for Little League and 20 mph for university professors playing slow pitch softball.* Ideal bat weight is specific for each individual, but it does not appear to be correlated with height, weight, age, circumference of the upper arm, or any combination of these factors, nor is it correlated with any other obvious physical factors.

To further emphasize the specificity of the ideal bat weight calculations, we must display individual statistics rather than averages and standard deviations. In Figure 41 we compare the ideal bat weight with the weight of the actual bat used by the players before our experiments. This figure shows that most of the players on the San Francisco Giants baseball team are using bats in their correct range. The dashed lines in this figure (derived from data and calculations not shown in this chap-

*The coefficient of restitution of a softball is smaller than that of a baseball, but this did not affect our calculations, because the ideal bat weight is independent of the value of the coefficient of restitution.

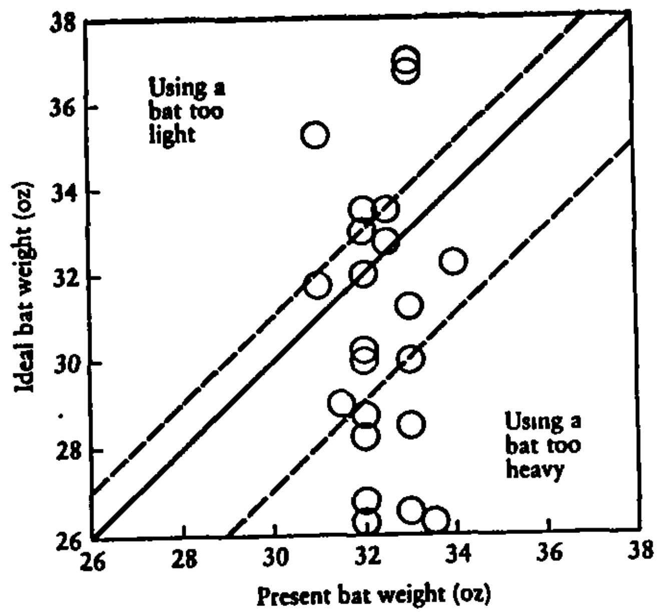

FIGURE 41. *Ideal bat weight versus actual bat weight for the San Francisco Giants. Most of them are using bats in their recommended range. [From A. T. Bahill and W. J. Karnavas,* Biological Cybernetics, *62:89–97, 1989.]*

ter) delineate the range of bat weights that we recommended to their management. We recommended that batters above the upper dashed line switch to heavier bats and that batters below the lower dashed line switch to lighter bats.

Not only is the ideal bat weight specific for each player, but it also depends on whether the player is swinging right- or left-handed. We measured two switch-hitters (one professional and one university ball player). One player's ideal bats weights were 1 ounce different and the other's were 5 ounces different. Switch-hitters were so different when hitting right- and left-handed that we treated them as different players.

Extrapolating from the equation

$$w_{2mbbs} = \frac{-w_1 A - \sqrt{w_1^2 A^2 - A w_1 (B - v_{1b}}}{A}$$

shows that the ideal bat weight also depends on pitch speed. Figure 42 shows this dependence of ideal bat weight on pitch speed for the ball player of Figure 39. This figure also shows the resulting batted-ball speed after a collision with a bat of the ideal weight. Such curves were typical of all our subjects.

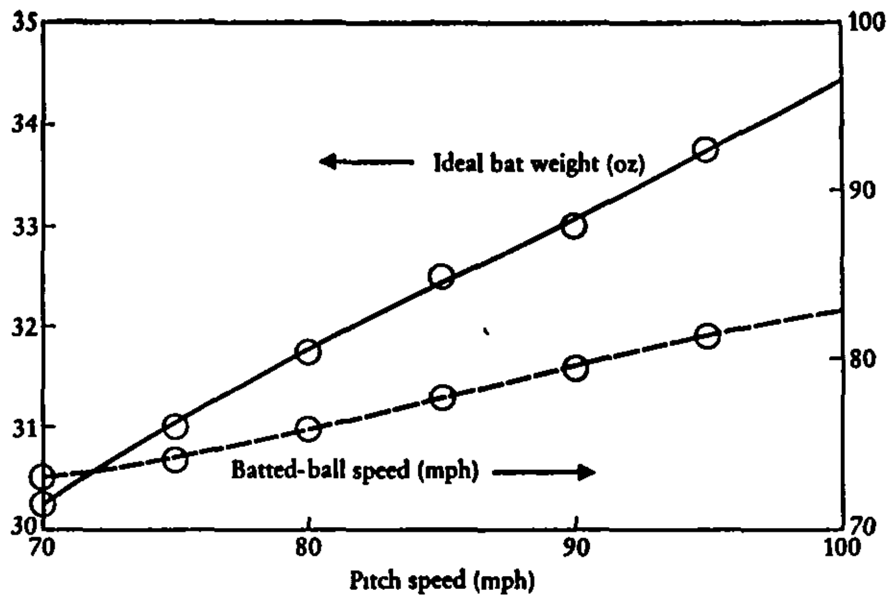

FIGURE 42. *Ideal bat weight and batted-ball speed both as a function of pitch speed for the professional baseball player of Figure 39. [Adapted from A. T. Bahill and W. J. Karnavas,* Biological Cybernetics, *62:89–97, 1989.]*

This figure shows that the ideal bat weight increases with increasing pitch speed. This means that even if they could swing 33-oz bats, Little Leaguers should use lighter bats, because the pitch speeds are lower. *However, when this figure is used to identify the ideal bat weight for a* particular individual, the results may seem counterintuitive. When the opposing pitcher is a real fireballer, the coach often says, "Choke up [i.e., get a lighter bat] so you can get around on it." In such situations the coach is changing the subjective weighting of bat control versus distance. He is asking the player to drop his criterion to 2 or 3 percent below maximum-batted-ball-speed bat weight so he can get better bat control. Since the batted-ball speed depends on both the pitch speed and the bat weight, the batter can afford to choke up when facing a fast pitcher, knowing that the ball will go just as far as it would if he were not to choke up when facing a slower pitcher.